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# Characteristics of some foam and foam-pesticide formulations for corn borer control

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Characteristics of some foam and foam-pesticide  
formulations for corn borer control

by

Din-Sue Fon

A Thesis Submitted to the  
Graduate Faculty in Partial Fulfillment of  
The Requirements for the Degree of  
MASTER OF SCIENCE

Major: Agricultural Engineering

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Signatures have been redacted for privacy

Iowa State University  
Ames, Iowa  
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## INTRODUCTION

More than ten thousand species of injurious insects are present in the crop fields of the entire world. Ecologically, these insects grow and thrive because man creates a good environment for them to live in. Man hence has to create an efficient means to control them.

In the United States, farmers are spending more than three billion dollars each year in an effort to reduce the losses caused by pests. Estimates are that costs will be even higher in the future.

Many methods of pest control are now in use. Chemical control methods are used extensively. Presently, spraying is the most common method of application of insecticides. However, ecologists believe that residues of these chemicals contribute to environmental pollution, while agriculturists doubt that spraying is an economical means of using the expensive chemicals.

The European corn borer was first found in the United States in 1917. The population of corn borers was reported increasing yearly. In Iowa, the state average in 1969 was 164 borers per 100 plants, but it increased to 241 borers in 1970. The control of corn borer is becoming of economic importance. Frye's survey (16) discovered that the number of the borer eggs increased with plant height. The larvae and cavities per plant were found greater on taller corn. In addition, most of the

hatched larvae of borer are protected by the sheaths of corn leaves. This raises more technical difficulties in borer control. The tiny particles of the spraying fog do not reach the protected plant areas. This reduces the efficiency of spraying and also causes unnecessary pollution. In this situation, foam pesticide formulations may be of benefit.

Although modern industrial advances and the requirements of commerce have raised foams of all kinds into positions of prominence for uses, such as fire fighting, foam fractionation, cosmetics, rubber and plastic, foam seems still a stranger to agriculturists. In Agriculture, foam was first applied in the frost protection of plants by contributing its blanket effect. Later, it was employed in herbicide application. Now, it is proposed to control insects. Some of the potential advantages of foam for corn borer control are:

1. The foam bubble, theoretically, will keep the poisonous vapor of pesticides attached longer to the plants and increase the possibility of killing the borers.

2. As the foam bubble stays on the lower parts of corn leaves, some poisonous liquid will drain out and run into the leaf sheath where the larvae of borers are feeding.

3. Because of lower surface tension of foam itself, the foam bubbles may cause a suffocating effect on borers.

4. Foam bubbles may be applied to particular parts of corn plants rather than to the whole plants as the sprayer does. Hence, less consumption of chemicals might be expected.

5. Because the chemicals are not carried through the air by wind, the foam-carrier method will reduce drift and minimize the pollution problem.

## LITERATURE REVIEW

## Classification of Foam

Many researchers have tried several different ways to classify foam. However, a generally satisfactory foam classification scheme still does not exist. Most researchers have defined foam for their own special purposes and no single method seems universally acceptable. Some variables to be considered in foam formation were the chemical nature of foaming agents, the liquids with which they might be used, aeration devices, the foam expansion ratio, storage temperature limitations, and the recommended use concentration of the foaming agents (44).

Bikerman (5 & 6) has mentioned two general methods--dispersion and condensation--which can produce foam. Many solid foams were manufactured by condensation with certain "blowing agents" added deliberately. The dispersion method mechanically introduced air or gas into the liquid, producing bubbles.

Nash and Fittes (33) divided foams into five groups for the fire-fighting use. These were chemical foam, fortified mechanical foam (fluoroprotein-based), all-purpose foam (alcohol foam), "light water" foam, and high-expansion foams. They were grouped in this way only because of the foam's individual characteristics and its special usage. Therefore, the group range expressed in terms of some parameters was not



available. However, Nash and Fittes further subdivided the last group by expansion ratio. They called the foam with expansion ratio from 50 to 500 medium high-expansion foams, and from 500 to 1,200 super high-expansion foams.

Jamison (21), in his study of stability of foams, described high expansion foams as two types, stable and unstable. The range of this subgrouping for fire-fighting was dependent upon the shrinkage of the foam height when overhead sprinklers were operated.

In his article "On a Classification of Foaming Solutions", Shorter, cited by Berman and Egloff (4), noted that classification of foam solutions was based on two distinct foaming phenomena: the nature of the process of the formation of the surface layer, and the manner in which the surface contributed to the stability of the liquid film.

Foams were generally classified into chemical and mechanical types (38). The chemical foams were produced by some chemical reaction with stabilizing agents present, which would be quite similar to the Bikermen's condensation method. Mechanical foams, on the other hand, were produced by blowing or beating air or gas through the foaming solution.

Ratzer's classification (40) had the same viewpoint as Nash and Fittes' did so far as the purpose of foams was concerned. But Ratzer did classify foams in a more reasonable way. He described foams as low expansion, high expansion, and alcohol resistant types, in which foam of expansion ratio from

6 to 10 was considered as low expansion type, and from 16 to 20 as high expansion type.

As McWhorter and Barrentine mentioned (29), Moilliet classed foams in three groups: unstable, metastable and solid. Unstable foams were of brief duration and collapse independently of internal drainage. Metastable foams were those in which the drainage of liquid from between bubbles eventually stopped. Solid foams were rigid and usually of plastic.

In practical applications, foams were often characterized as "dry" and "wet" depending on the liquid-air ratio (48). McWhorter and Barrentine (29) explained that wet foams contained more water with lower expansion ratio and were generally produced mechanically; while the dry foams were produced by blowing a stream of air through a thin film of solution. Nevertheless, the dry foam still could be obtained when a stable wet foam became drier as the liquid drained out of it (48). Braud and Chesness (8) further defined the wet foam by expansion ratio of less than 20 and by the liquid flow rate of greater than 28 lb/min per square foot of screen area. Dry foams were also divided, according to Braud et al. (7), into homogeneous and non-homogeneous sections by setting a limit of liquid flow rate at 16 lb/min. per square foot of screen area.

Schwartz and Perry (48) grouped foam generating methods into two classes: a) foams generated by shaking, beating, or whipping air into the solution mechanically, and b) foams generated by blowing a stream of air or gas through the solu-

tion. However, the first type of generators was criticized because it was too dependent on the individual operator (59).

### Characteristics of Foams

Schwartz and Perry (48), in their article "Surface Active Agents and Detergents", outlined the properties of a foam, which were of greatest technical interest, as follow: a) foam production rate, b) foam volume, c) foam stability, d) foam drainage, e) foam consistency and viscosity, f) bubble size and distribution and g) foam expansion. Chesness and Braud (10) and Thomas (56) added the foam thermal property for their frost protection experiments and fire-fighting tests respectively. In addition, Braud et al. (7) introduced three more factors--air capture ratio, homogeneity and pressure drop across a screen--in their foam characteristic measurements. They also reported that an air capture ratio less than 100% resulted in non-steady foam flow because of slugs of air which emitted. In the study of the streaming potential of foam, Raza (42) measured the following new quantities: streaming potential, current, flow rate and foam quality. Foam quality, according to Raza's definition, was the same as air capture ratio and also sometimes called as air volume factor (22). Amiel (1) measured the range of foam quality in the interval of from 0.80 to 0.96 in his experiment.

Friedrich (14), on the other hand, measured the conduc-



tivity of foaming agents, and found the conductivity of foam was a function of concentration and temperature. Shih (52) discovered that volumetric foam density was correlated with the electrical conductivity ratio of foam to liquid, which was in agreement with the discovery of Bikerman (5). Fanlo (13) measured the specific conductance of foams as an electrolyte was added to the solution of surfactant. He then used this technique to study the foam drainage both statically and dynamically. Schwartz and Perry (48) found, by using a foam generating device of the air-blowing type in which several different foam parameters could be measured at the same time, that electrical conductivity measurements on foams and on their generating solutions afforded a means for calculating the foam expansion ratio. Unfortunately no more details were disclosed.

#### Bubble Size and Distribution

Any report on the topic of foam would be incomplete without noting the effect of bubble size (49). Shansky (49) considered that breakage of the foam bubble would depend upon the area exposed to the atmosphere and/or other bubbles and, therefore, because of the Gibbs angle, the smaller the bubble, the longer its life. Ross (47) and Glium and Shelomov (17) all exerted much effort in discovering the theory of foams and bubbles. They developed a mathematical model for the



radius and surface tensions of bubbles in terms of other factors.

The photomicrographic technique has been applied in measuring the distribution of bubble sizes. By this technique Chang et al. (9) discovered that the larger bubble would grow but the smaller bubble would shrink as a function of time. Shih (52) also utilized this photographic method to detect the coalescence of the bubble in an operating foam column and found that the bubble breakage largely depended on the type of bubbles and the pool concentration. Augsburger (2) also employed this technique to determine the size of aerosol foams and pointed out that small bubbles were associated with higher consistencies and had to be related to the foam specific surface. Post (39) photographed foam bubbles through the wall of a Pyrex box in developing a correlation between the bubble diameter and time. But Lemlich (26) pointed out that the potential weakness of this method was that measurements were subject to several sources of error including the distortion of individual bubbles and bubble sizes at the wall and the statistical bias inherent in sampling a size distribution at a plane rather than by counting through its volume. He then suggested that bubble diameters be measured photographically in the liquid pool, utilizing an external surrounding pool bounded by flat walls to eliminate the optical distortion. To overcome this difficulty, Chang et al. (9) employed a "quick-freezing" technique with liquid oxygen, and photographed the bubble

distribution before and after foams were frozen. They discovered that the average bubble size obtained with 6% Mearl-foam solution was inversely proportional to expansion ratios, and the bubble size and the size distribution were affected not only by the expansion, the nature of the foaming agent and its concentration, but also by the type of the generating system, the inlet air pressure and the height or the nature of the packed column.

### Foam Stability

Great progress has been made within recent years in understanding the phenomenon of foam stability. Sydney, stated by Schwartz and Perry (48), developed two mathematical expressions: one for the average lifetime of gas or air,  $L_g$ , and one for that of the liquid in the foam bubble,  $L_\ell$ :

$$L_g = \frac{1}{G_o} \int_0^{G_o} t \, dG \quad (1)$$

$$L_\ell = \frac{\ell}{V_o} \int_0^{V_o} t \, dV \quad (2)$$

Where  $G_o$  and  $V_o$  are the volume of the gas and the liquid respectively.

A standard test procedure for foam mechanical stability in aircraft rescue and fire fighting vehicles has been included by the NFPA (54). This procedure emphasized the stability of foams during a fire. Rivkind (44) realized that the stabil-

ity of foams, especially for the fire fighting, should be a function of four kinds of resistance, namely, a) resistance to spontaneous collapse, b) resistance to thermal radiation or heat resistance, c) resistance to chemical or solvent attack, and d) resistance to mechanical disruption.

Merrill and Moffett (30), by modifying the apparatus that was developed by McBain, Ross and Schutz, measured the foam stability with time method, which was defined as the time required for half the surface area to become free of bubbles. Bikerman (5), meanwhile, has suggested the term "foam height" to describe the stability of foams. He defined the foam height as the difference in level between the top and the bottom of the foam column in a graduated tube. Stephan (55), following this idea, designed his own apparatus and compared several commercial bubble baths by the foam height with respect to time.

### Foam Drainage

Jacob et al. (20) considered that the stability of aqueous foams was determined by two different phenomena: the rate at which liquid drained from a foam and the rate at which the body of foam bubbles broke down. Presumably, they thought the drainage from the foam bubble was almost completely unaffected by the bubble breakdown. They derived two equations in representing the drainage rate,  $R$ , and the drained liquid volume,  $V$ :

$$R = \frac{\beta}{(\gamma t + 1)^{3/2}} \quad (3)$$

$$V = \frac{2\beta}{\gamma} \left( 1 - \frac{1}{\sqrt{\gamma t + 1}} \right) \quad (4)$$

Where  $\beta$  and  $\gamma$  are both constants with implicit units. The constant  $\beta$  corresponds to the initial drainage rate; while the time dependence of the drainage rate is a function of  $\gamma$ . In proof of this theory, they blew a quantity of controlled air into the bottom of a calibrated cylinder which contained a certain quantity of surfactants. Although the application of these two equations was subject to some inaccuracies, they found that only slight adjustments were necessary to obtain the optimum fit to the drainage curve with these equations. After examining their experimental data, they concluded that foams with the highest expansion exhibited the lowest drainage rate.

Bikerman (5) considered that the liquid in a cylinder drained because of gravitation and suction by Plateau's border. He constructed a flask of 1,900 cc with 100 cc of liquid inside, determining the rate of foam drainage, and designed the term "foam number" to scale the quantity. He also listed several typical equations to express the rate of drainage with respect to time for different possible conditions. One of these equations that have often been used by other earlier researchers is:



$$V = V_0 ( 1 - e^{-kt} ) \quad (5)$$

Where  $V$  = the cumulative drainage at time  $t$ .

$V_0$  = total drainage (at time  $t = \infty$ ).

$k$  = a constant.

This equation usually held true for the foams of beer, wine, saponins, aerosols, and lauryl sulphonic acid (49).

In order to find the effects of water hardness on the drainage rate of high-expansion foams, Thompson (57) developed a fringe method by observing the movement of interference fringe orders in the film, formed in a  $45^\circ$  tilting frame, of a foaming solution. From this experiment he concluded that a useful figure of merit for the water-retaining ability of a foam would be the half-drainage time, i.e. the time taken for one half of the water to drain from the foam. He also found that, with the exception of only few certain agents that gave slower draining films in slightly hard water than in soft and distilled water, the usual effect of hardness in water was to accelerate the normal process of drainage. Following this half-drainage time idea, Reichard et al. (43) worked on their foam generator experiment and discovered that some of foams showed a very little decrease in volume when 50% drainage time occurred.

However, the most common method in current use in the U.S. and in Canada for measuring foam drainage was the so-called "quarter drainage time" (44, 37, 38, 8), or, the time to drain

25% of the originally contained liquid from the foam. Quarter drainage time served as a convenient means to characterize foams but still could not provide an absolute measure for the drainage property of foams (44).

Since the bubble films (faces) met three at a time to form capillary pores, Lemlich (26) thought drainage in such a foam occurred primarily through this capillary rather than through the films. By using dimensional analysis, he derived an equation for the dry foam in his foam fractionation analysis as follows:

$$Q = \frac{G^2 \mu}{A g \delta d_o^2} \quad \bar{a} \left( \frac{\mu_s^3 G}{\mu_s g \delta A} \right) \quad (6)$$

In which

$$d_o^2 = \frac{\sum n_i d_i^3}{\sum n_i d_i} \quad (7)$$

Where A is the cross section of the column;  $\delta$  is liquid density;  $\mu_s$  is surface viscosity;  $\mu$  is viscosity;  $d_o$ , average bubble diameter;  $d_i$ , diameters of certain bubbles;  $n_i$ , number of bubbles; G, the volumetric flow rate of gas; g, gravitation force and  $\bar{a}$  is a function.

Generally, in the frost protection work, drainage is undesirable. Braud and Chesness (8) pointed out that the evaporation of the liquid from bubble walls caused loss of foam weight, and its magnitude would be significant in a windy, dry atmosphere. However, with a water-binding agent or stabilizing

agent, the drainage did not begin immediately and sometimes could extend as long as 36 hours.

### Foam Expansion Ratio

Foam expansion was a useful measure for evaluating aqueous foams. As Fry and French have cited (15), Clark found that a fire-fighting foam could be almost completely defined by its expansion factor (or expansion ratio) and its ultimate shear strength. The NFPA Standard on Foam Extinguishing Systems (No. 11) has taken this factor into consideration. According to Rivkind's report (44), the measured foam expansion value, obtained by using a foam collecting board, varied significantly for different combinations of foam composition and concentration.

For fire-fighting foams, low-expansion foam was favored. But for the agricultural use, it is sometimes quite different. Braud and Chesness (8) used a foam expansion ratio of about 30 in their frost protection tests. McWhorter and Barrentine (29) both performed an experiment of foam for herbicide application. They created 300 to 400 gals of foam from 1 gal of water. Similarly, Reichard et al. (43) have generated foams with expansion ratios greater than 300 to 1 during their experiments. But they admitted that with these higher expansion ratios, it was not possible to keep these foams on target even when wind velocities were as low as 4 miles per hour.

## Foam Production Rate

In general, foam expansion was proportional to the air flow rate. Metzner and Brown (31), in their study of mass transfer of foam, found that there existed two distinct regions --they called them regions of quiet and turbulent foaming. In the quiet region (or low-gas rate region), the pressure drop decreased as the gas rate increased and so did the expansion. At the same time, the bubbles appeared uniformly distributed and smoothly flowing. In the turbulent (or higher gas rate) region, pressure drop increased with increasing gas rate. The foam generated within this region appeared considerably swirling and the rupturing of groups of bubbles increased markedly with increases in gas rates, causing violent swirling and breakup of foam. Accordingly, the foam expansion decreased with increasing gas rates in this region.

Numerically, the foam nozzle with 25 cfm air flow rate, designed by McWhorter and Barrentine (29), produced 21,000 gals of foam per acre, which covered an acre with approximately 0.75 inch of foams. According to their experimental results, if the air flow decreased to 20 cfm the foam production rate would decrease approximately 14%; while if increased the air flow to 41 cfm it would increase the foam production about 10%. In fire-fighting foams, three thousand gals per minute was reported (37).

Reichard et al. (43) have exerted much effort to finding



the production rate of a foam generator with several variable parameters such as: percentage of foaming agent (PF, %), air flow rate (QA, cfm), number of screens (SC), area of individual openings in screen (A, in<sup>2</sup>), and square of diameter of screen (DSQ, in<sup>2</sup>). By using a multiple regression analysis, they derived the following equation containing all the variables. In which the production rate (QF) was in cfm.

$$\begin{aligned} QF = & -0.634 + 0.213 \text{ PF} + 0.0409 \text{ QA} \\ & -0.0114 (\text{QA})^2 + 0.0109 \text{ SC} \\ & -0.0212 \text{ A} + 0.0160 \text{ DSQ} \end{aligned} \quad (8)$$

#### Uses of Foams

Foam has many practical applications. Many articles about foams for fire extinguishment use have been discussed (34, 37, 44). Some researchers were trying to use foam plugs to fight coal mine fires and dust (27,28). Foams were also used to cover runways for aircraft emergency landings for fuel-ignition-suppression (36, 35). Foams have also been used in many chemical industries such as in the textile industry and biochemical applications.

The foam fractionation technique has been adopted in separation of materials such as kaolinite and silica, and rare-earth elements (45, 61). Sewage disposal plants used foaming techniques to separate detergents from the incoming sewage

Now, the advantages of foams are of great interest to

agriculturists, too. Foams were first applied for frost protection of tomatoes and coleus (53). Later use on strawberries was reported (12, 8, 10). McWhorter and Barrentine (29) were apparently the first to apply herbicides in foam. Braud et al. (7) listed some interesting possibilities in insect and pest control, to which foams may soon be applied:

- a. Carrier for herbicides, insecticides, clearing agent, and abscission chemicals.

- b. Defoliant and evaporation suppressant.

- c. Soil cover for fumigation and soil amendment to improve structure.

- d. Suspension medium for solid particles, fertilizer, seed, etc.

- e. Farm marker.

However, foams in certain situations are not beneficial. Examples are dishwashing machines, distillation of soap dyes, glycerine recovery, mash distillation, paper making, glue making, emulsion paint manufacture, and atomic reaction boilers.

## OBJECTIVES

Before the insecticidal foams can be successfully applied to corn borer control, many technical problems still exist and must be solved. Nobody knows what kind of foam is best for this purpose. Neither do we know what foaming agents or foaming apparatus are most suitable. The objectives of this research are:

1. To classify foams according to the parameters that describe foam quality.
2. To determine what effect changes in these parameters have on foam quality.
3. To determine the physical properties of foams and how these properties change with time.
4. To investigate the effectiveness of different types of foam as insecticide carriers for the corn borer control.

## INSTRUMENTS AND MATERIALS

The experimental equipment consisted of a foam generator, air flow system, liquid pumping system, and the measuring instruments. Air flow rate was controlled by a universal electric motor with variable voltage control. The water pump was driven at constant speed by an a-c motor and the liquid flow rate was adjusted by a pressure regulator. The measuring instruments included containers, scales, calibrated cylinders, beakers, stop watch, Plexiglas box, and an X-Y plotter.

The X-Y plotter was important in recording the data of foam conductivity with respect to time. A high-speed camera with polaroid film was used to aid observation of the falling foam from the generator. The polaroid film would permit visual foam comparisons to be made very quickly and aid in assessing reproducibility of foam quality.

## Foam Generator

The foam generator used in this experiment was basically the same as the one that Reichard et al. (43) have employed in their experiments, with some modifications. It consisted of a Plexiglas cylinder, a disc cone spray nozzle, three copper screens and a V-shaped discharge box. Details of each component are shown separately on Figure 1. The Plexiglas cylinder was a chamber that provided a passage for both air and liquid spray particles. It was 12 inches long,  $5\frac{1}{2}$  inches

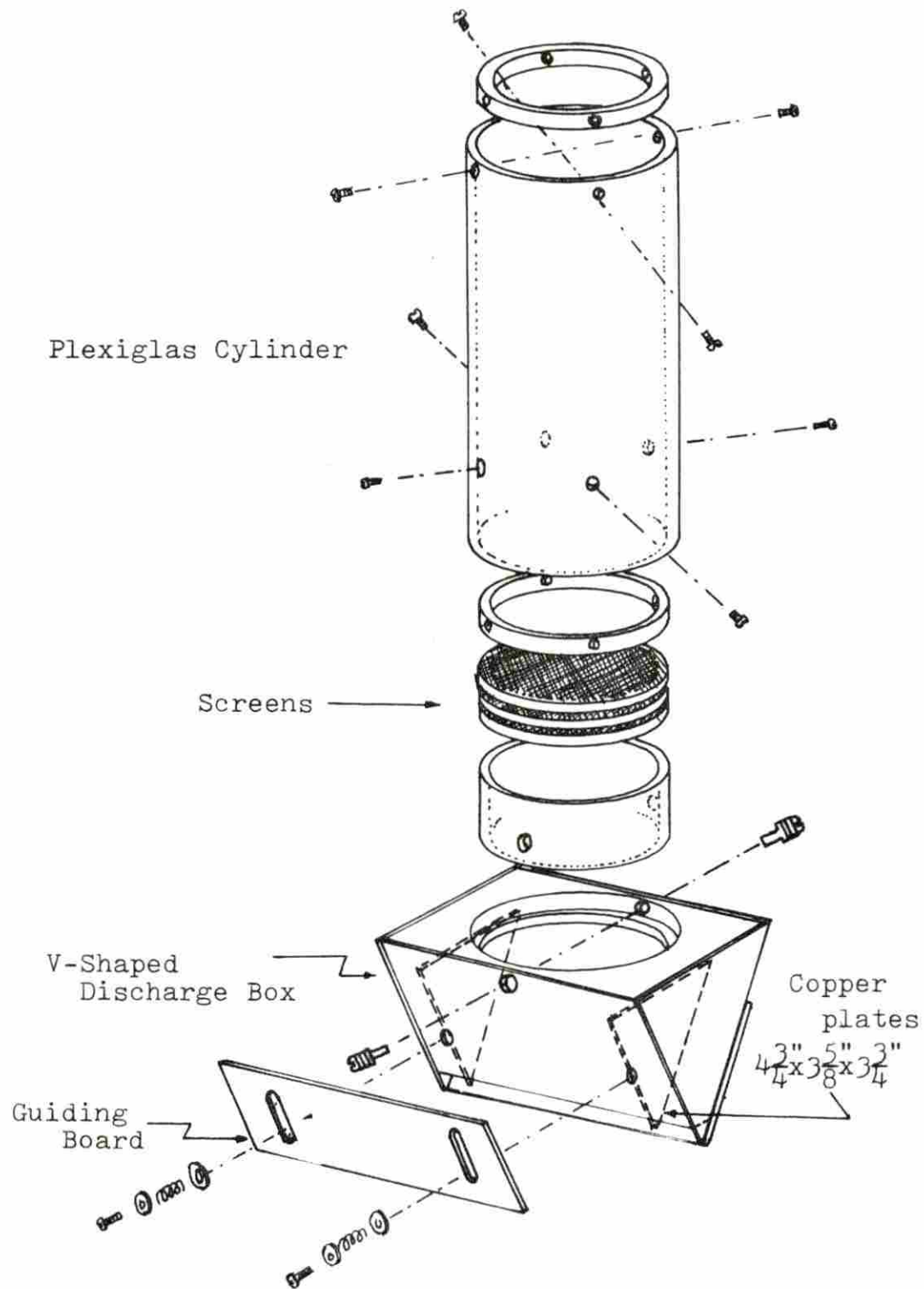


Figure 1. Components of the foam generator

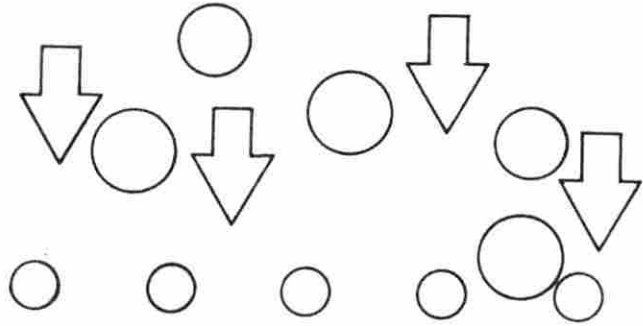


in inside diameter and  $\frac{1}{4}$  inch thick. The V-shaped discharge box was another small chamber for mixing and redistributing foam bubbles homogeneously. The sloping planes at both sides of this chamber then guided the foam bubbles downward and forced them passing through an 8-inch long and  $\frac{1}{2}$ -inch wide slit opening, producing a plate-like flow of foam column. Thus, it increased the area coverage when foam was sprayed on plants or on the ground. The guiding boards on both sides of this box were used to control the thickness of the foam column and the speed of the foam flow.

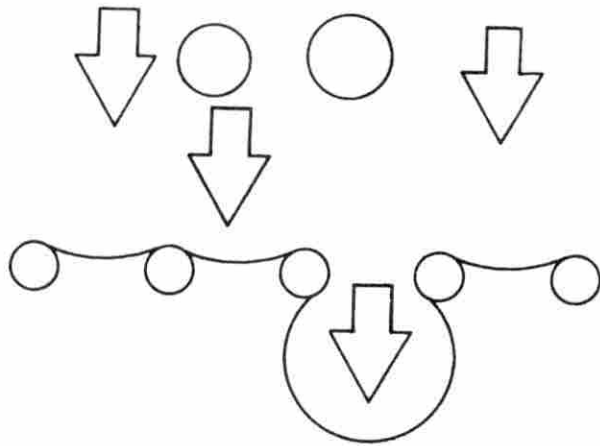
Inside the discharge box, there were two triangular copper plates with  $4\frac{3}{4}$ " on one side and  $3\frac{3}{4}$ " on the others. Both plates were five inches apart. They provided a means for measuring the foam conductivity dynamically.

The principle of generating foam by this apparatus was the same as the second method that Schwartz and Perry (48) have mentioned before. A stream of controlled air was blown downward through a set of screens that were already wetted by spraying the solution of foaming agents. Figure 2 illustrates an exaggerated action between air and film solution when both of them hit screens. In Figure 2 the arrows represent the air flow rate and circles the tiny drops of solution spray. Theoretically, when the tiny drops strike on screen wires, they will spread as a thin film between wires. Because of low surface tension of the solution, bubbles result. This action will produce foam bubbles continuously behind the screen.

- (a). Tiny water particles hit the wire and spread as a thin film.



- (b). Air pushes the film downward.



- (c). The push of air and the surface tension of the solution expedite the bubbling result.

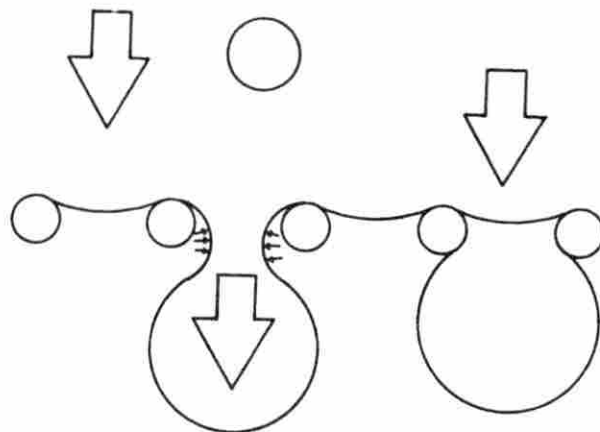


Figure 2. Principle of producing bubbles between screen wires

The distance between the spray nozzle and the screen was an important factor in foam production. This distance was a function of the nozzle spray angle and the diameter of screens. The distance should be so adjusted that all spraying particles could hit and cover uniformly all the screen area. Both too great and too close distance would cause a loss of efficiency of foam generation. The best choice of nozzle is the solid-cone type. Use of the hollow-cone type of nozzle would produce large bubbles in the central part of the foam column and produce less foam. In this experiment, Delavan disc cone spray nozzle, DC 3-45, with capacity of 0.23 gpm at 40 psi liquid pressure, was used.

To operate the foam generator successfully, a correct value of each parameter is of extreme importance. The liquid pressure can be preset to a desired value, but practically it was always adjusted while the foam generator working. Adjustment of the air flow rate required care because of slow response in the manometer. Two separate switches were then provided: one for the fan motor and one for the pumping motor. In operation, the fan motor would be turned on first, and then the pumping motor. The water level of the manometer would go higher than the desired value and then drop to the desired value as soon as the pumping motor was turned on.

However, the first streaming of foam produced right after the generator started was not recommended for measurements. A waiting period was necessary. This was specially true when



foam solution was changed. The former foaming agent would stay in the pumping system and a solution of unknown composition would then result. Emphasis on this point was particularly obvious when the foam generator was operating at a low liquid flow rate, because a large quantity of the residual solution would return to the tank and mix with the new solution under the function of the pressure regulator.

A similar caution had to be exercised when cutting off the foam generator. The fact was that both motors could not stop as soon as their switches were off. Actually, they decreased their speed gradually, and therefore the foam produced during this period was completely out of control. To avoid this unpredictable foam being included into the measuring system, samples had to be collected under normal operating conditions. A revolving stand would serve for this purpose.

#### Air Flow Meter

Air was supplied by a five-inch diameter electric fan, of which the speed was controlled by a 120-volt STACO variable autotransformer, as shown on Figure 9a. The output voltage of this transformer could be varied from zero to 140 volts and directly supplied to the fan motor. However, the practical voltage only ranged from 20 to 40 volts during the whole experiments. Excess voltage would generate too much air and produce broken bubbles; while voltage lower than 20 volts was

not enough to overcome the bearing friction of the fan motor and the motor would not start, or start slowly. A relationship between the output voltage of the autotransformer and the water level of the manometer is shown on Figure 3. Curves are plotted for conditions with and without pumping motor running. Reasons for this discrepancy may be explained as follow:

a). The line voltage dropped some small amount when two motors were operating simultaneously.

b). The plugging effect of foam in the chamber increased the back pressure and thus decreased the pressure difference across the manometer.

To measure the air flow rate, a cylinder with a perforated metal orifice plate which has been discussed in Instrument News (51) was used during early experiments. However, to improve the metering accuracy, another flow meter was designed for the same purpose. Figure 4 shows the details of this new flow meter.

This flow meter was a combination of venturi and orifice meters, or so-called flow nozzle type. It consisted of a pipe, 12 inches long and  $1 \frac{13}{32}$  inch in diameter, and a small cylinder with a hollow tapered through the central axis. The air flow rate was measured by the difference of the water level in a U-tube manometer. The difference of the water level, theoretically, can be expressed in a mathematical form. According to Whitaker (58):

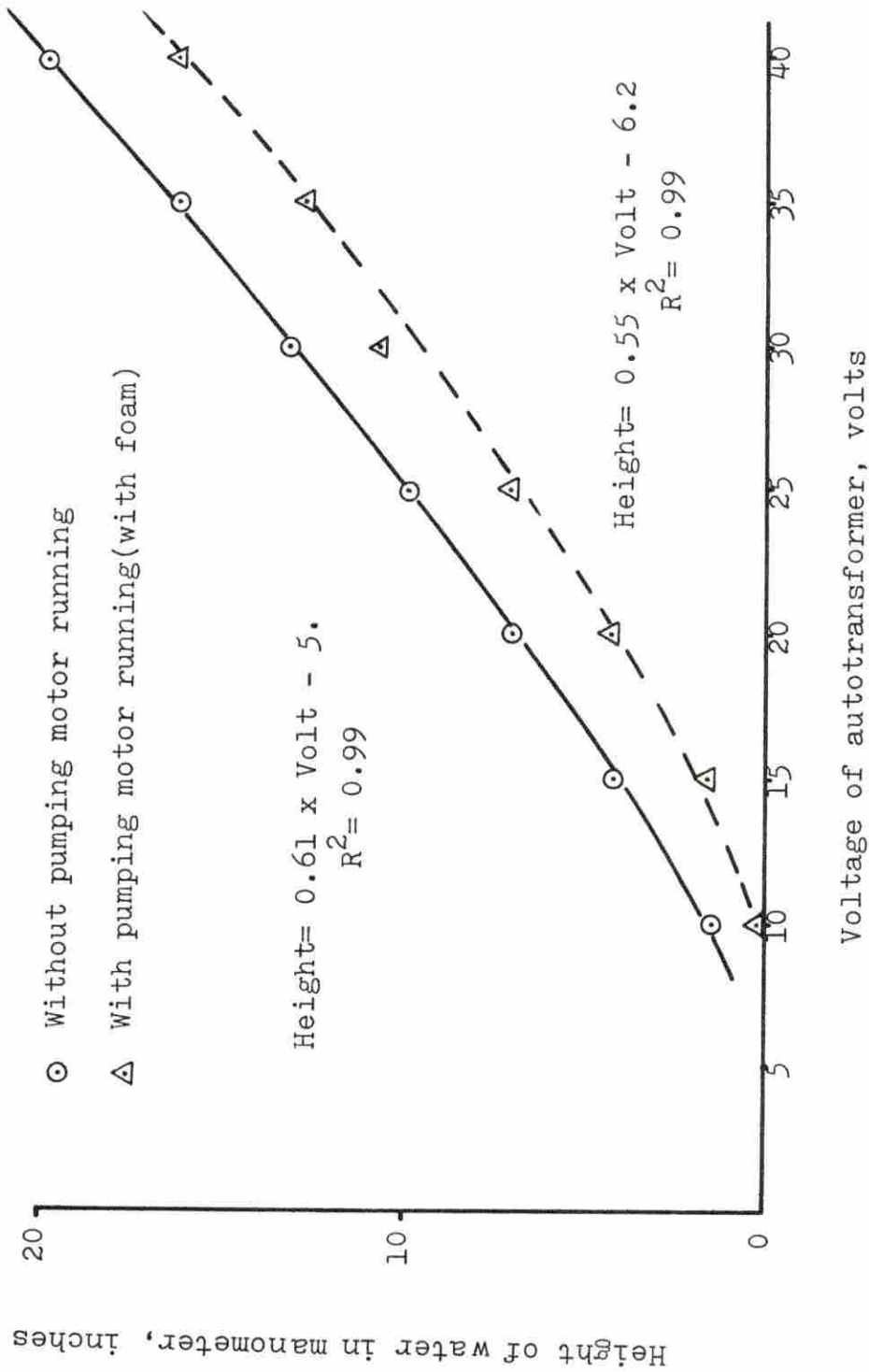


Figure 3. Characteristics of autotransformer and manometer

$$Q = C_d A_2 \sqrt{\frac{2 (P_1 - P_2)}{d_a (1 - (A_2/A_1)^2)}} \quad (9)$$

Where  $A$  = air flow rate, in cfs.

$C_d$  = discharge coefficient.

$A_1$  = intake area,  $\text{ft}^2$ .

$A_2$  = discharge area,  $\text{ft}^2$ .

$d_a$  = density of air, slugs/ $\text{ft}^3$ .

$P_1$  = pressure at intake area,  $\text{lb}/\text{ft}^2$ .

$P_2$  = pressure at discharge area,  $\text{lb}/\text{ft}^2$ .

Equation 9 can be modified by substituting the difference of water level in the manometer :

$$P_2 - P_1 = d_w g h \quad (10)$$

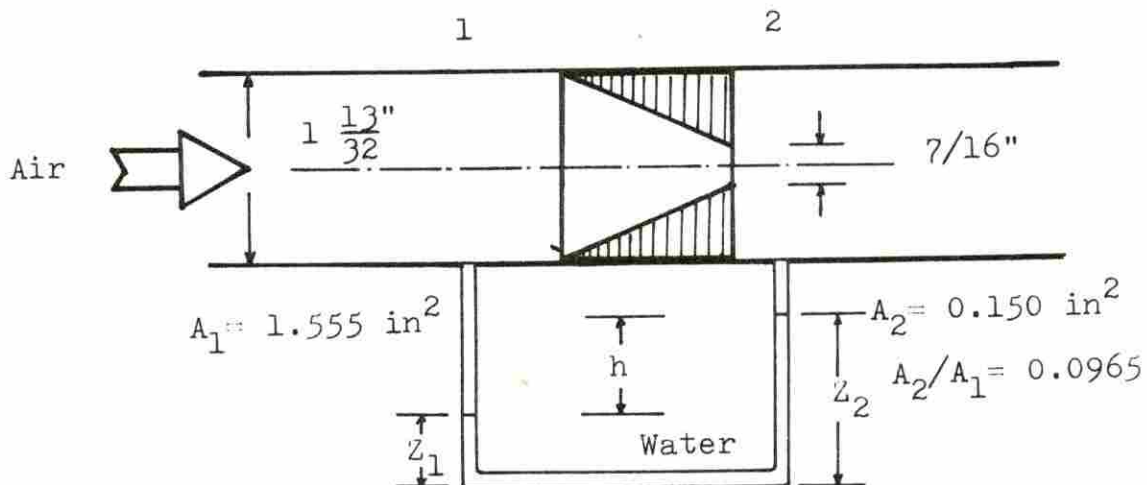


Figure 4. Details of the flow meter

Here  $d_w$  is the density of water and  $h$  is the water level in the manometer. Equation 9 then will become:

$$Q = C_d A_2 \sqrt{\frac{2 d_w g h}{d_a (1 - (A_2/A_1)^2)}} \quad (11)$$

At standard pressure and  $70^\circ$  F room temperature,  $d_a = 2.33 \times 10^{-3}$  slugs/ft<sup>3</sup>;  $g = 32.2$  ft/sec<sup>2</sup>;  $d_w = 1.94$  slugs/ft<sup>3</sup> and  $A_2/A_1 = 0.0965$ . Equation 11 can be simplified:

$$Q = C_d \times 4.19 \sqrt{h} \quad (12)$$

The units of  $Q$  and  $h$  in equation 12 are cfm and inches respectively.  $C_d$  in this case is about 0.45.

Actually this flow meter was calibrated directly against a standard Meriam Laminar Flow Meter (Model 50 MC 2, the Meriam Instrument Co.). The calibration results of this flow meter show on Figure 5.

The fan used was a type of tube-axial fan; air was sucked in through the flow meter, fan and then the motor windings. It finally reached the Plexiglas chamber for foam generation. The windings and rotor of the motor and the components of the foam generator are arranged as in Figure 6.

#### Water Pump

The water pump was a self-priming roller pump. It was driven by a  $\frac{1}{4}$ -hp. single-phase repulsion motor with a speed of

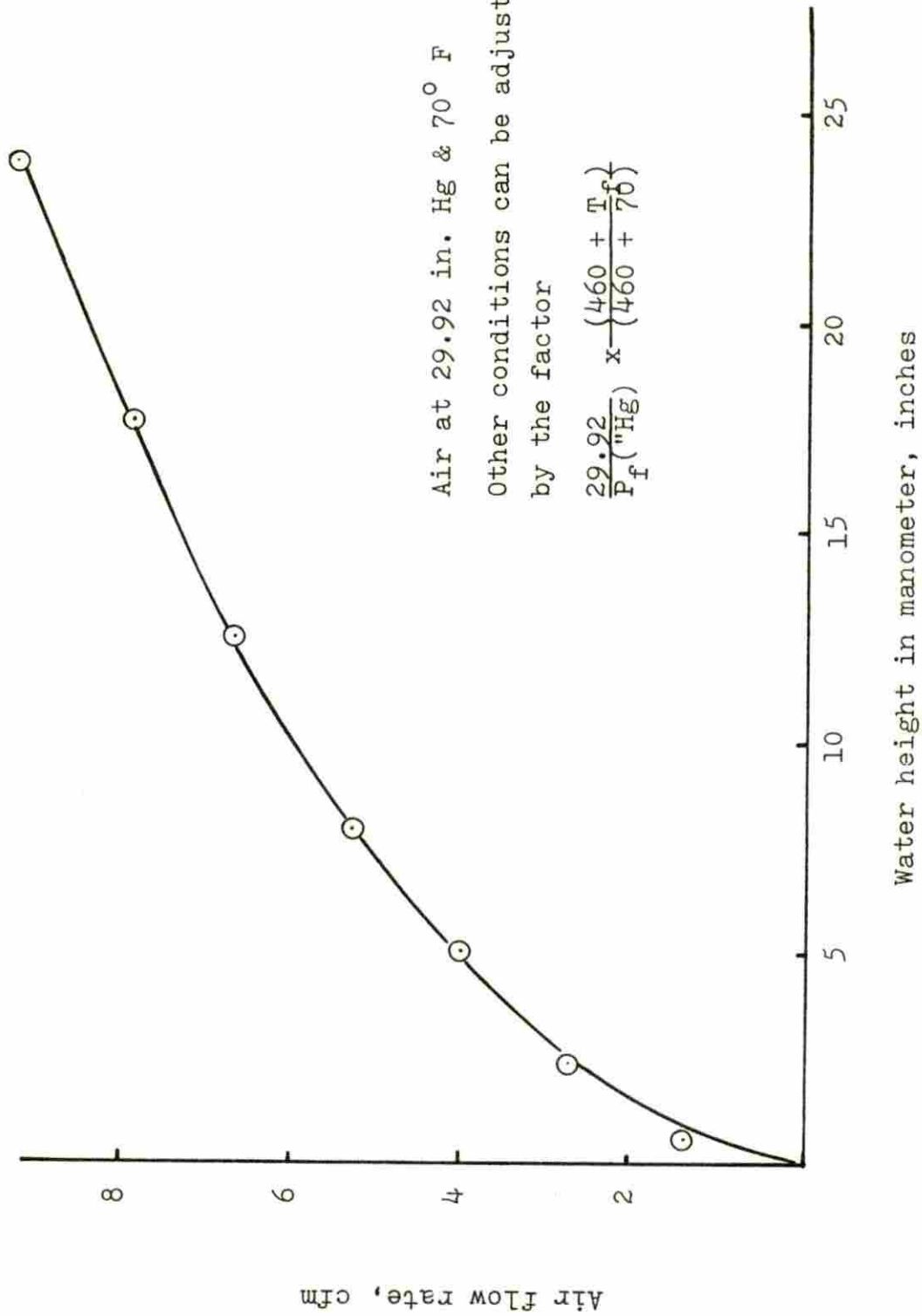


Figure 5. Relationship of air flow rate and water level in manometer



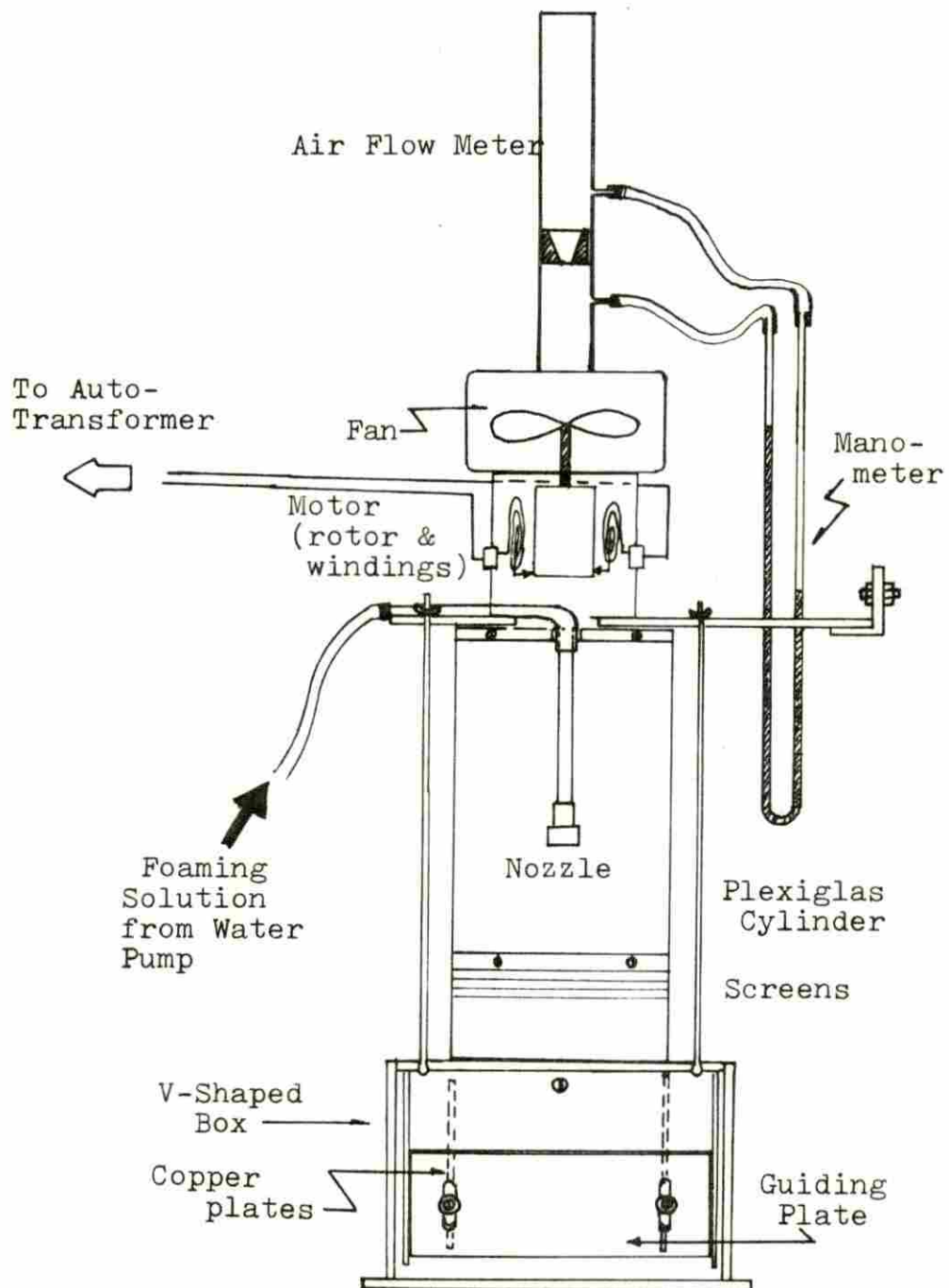


Figure 6. Sketch of air flow system and foam generator

1,750 rpm. Motor and pump were coupled by a V-belt drive with a ratio of 1.35:1. Accordingly, the speed of the pump would be 1,300 rpm under normal conditions.

A spring type pressure regulator controlled the amount of liquid in the line to the nozzle and returned the remaining liquid to the storage tank through a by-pass line. The returned liquid also produced an agitating effect on the liquid in the storage tank.

A 100 psi pressure gage was installed on the downstream side of the regulator so that it could quickly respond to the exact pressure as the regulator was adjusted. The useful pressure range was generally from 30 psi to 80 psi. Pressure higher than 80 psi would cause serious belt slippage and unstable pressure readings. However, pressure lower than 30 psi could not produce foams of suitable quality and quantity.

The relationship between the liquid pressure and the liquid flow rate is shown on Figure 7 and can be expressed as:

$$Q_{\ell} = 0.00805 + 0.03435 \sqrt{P} \quad R^2 = 0.9985 \quad (13)$$

Where the liquid flow rate,  $Q_{\ell}$ , is in gpm and the pressure,  $P$ , is in psi.

### Scale and Containers

Three different sizes of plastic containers were used in the experiment to determine the foam expansion ratio. It was also intended to investigate whether the container volume



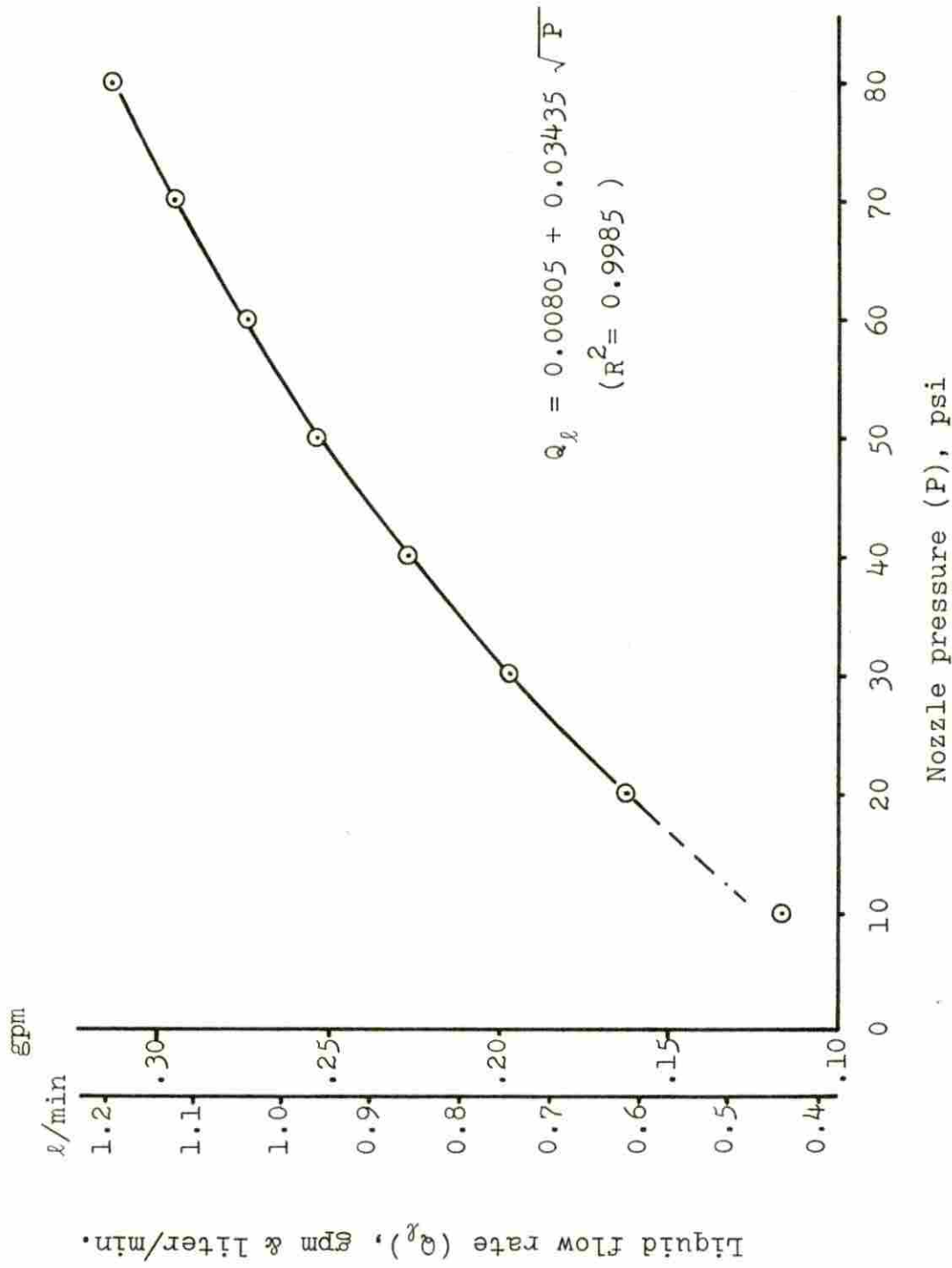


Figure 7. Relationship between the liquid flow rate and nozzle pressure

Table 1. Sizes of containers for measuring foam expansion

Type of container	Dimensions (upper dia. + lower dia.) x ht.	Volume	Net Weight
A	( $31\frac{3}{4}$ " ) x 12"	2.46 ft <sup>3</sup>	--
B	( 8" + $7\frac{1}{4}$ " ) x $6\frac{7}{16}$ "	4,750 cc	155 g.
C	( $6\frac{3}{4}$ " + $5\frac{5}{8}$ " ) x $4\frac{3}{16}$ "	2,000 cc	55 g.

affected the indicated expansion ratio. All these three containers were made of plastic to keep their weight low with respect to the foam weight and, therefore, to reduce the possible errors in measurements.

A careful study of the measurement of foam expansion ratio shows that smaller containers would measure the low expansion foam or the watery foam quite well without introducing any serious errors in the measurement, but they could not successfully measure the high expansion foams. In the actual case, some ambient air was occasionally entrapped in the small container during the foam-feeding process, causing an upward bias in the indicated expansion readings. This would be particularly true when the high expansion foam or the "dry" foam was measured. This high expansion foam could not flow very well to fill the void space in the container. However, the situation for the large container was completely reverse. It was successful for measuring the high expansion foam but not for the low expansion. The heavy drainage and bubble breakage of the low expansion foam reduced the foam volume rapidly

during the feeding procedure.

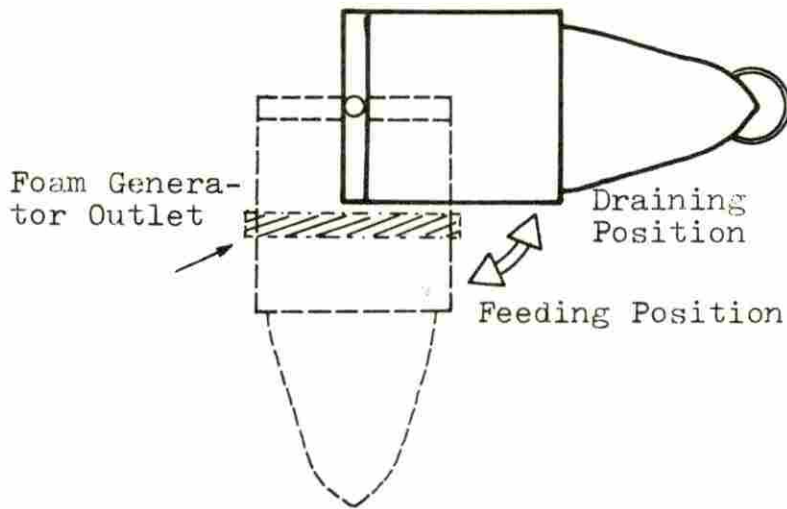
For ease of reading the expansion ratio, the scale was recalibrated directly in terms of expansion ratio. This was especially convenient for a field study.

#### Plexiglas Box and Stand

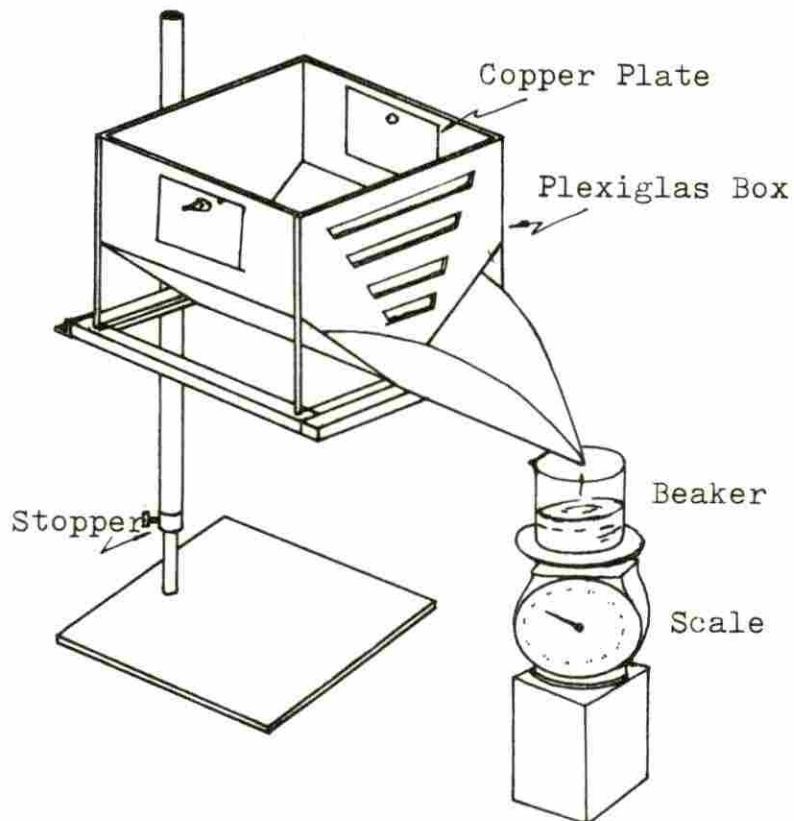
A Plexiglas box with size of 12"x12"x12" and  $\frac{3}{8}$ " thick was designed to collect the fresh foam as soon as it was produced. Details of the box are illustrated in Figure 8. The bottom of the box was shaped into a V-ditch to facilitate the foam drainage. The draining liquid, passing through the bottom hole, would be guided by an aluminium V-shaped plate to a beaker.

Two copper plates (5"x6") were attached on the opposite walls of the Plexiglas box to measure the conductivity of foam during the decaying and draining procedure. Each plate had  $\frac{3}{8}$ " away from walls, and the exact distance between these two plates was  $11\frac{1}{4}$ ".

A revolving stand provided a seat for the Plexiglas box and a means of quick box-switching control. The whole stand consisted of a long tube with a wooden seat, a ring stopper, and a steel bar that was fixed on a support. The swing action was accomplished by turning a  $1\frac{1}{4}$ " tube with respect to a 1" steel axle bar (as shown on Figure 8a). The stopper would help adjust the height of the seat and the Plexiglas box.

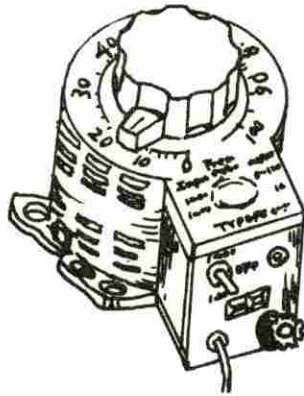


(a). Two positions of the Plexiglas box(top view)

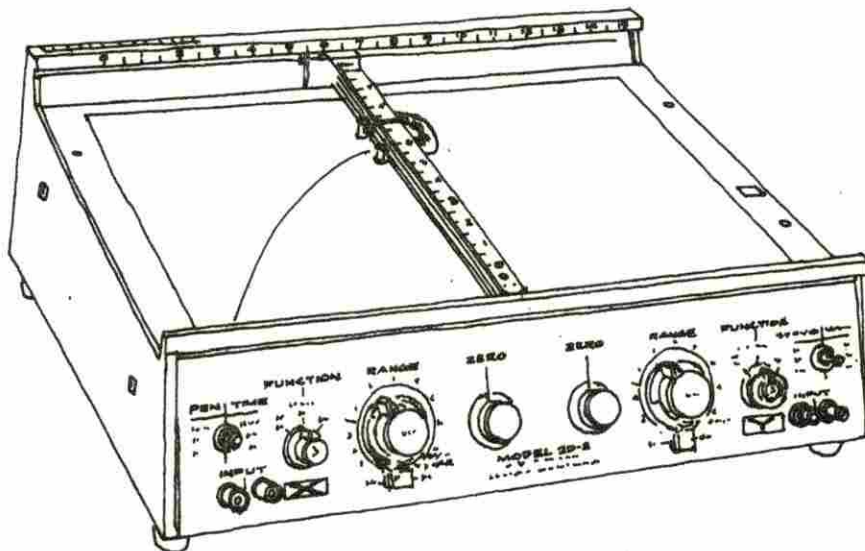


(b). Plexiglas box in draining position

Figure 8. General view of Plexiglas box and its stand



(a). SATCO variable autotransformer



(b). AUTOGRAF model 2 D-2 X-Y plotter

Figure 9. Sketch of an autotransformer and an X-Y plotter



### X-Y Plotter

The model 2 D-2 AUTOGRAF X-Y recorder, manufactured by F. L. Moseley Co., was employed for plotting the foam characteristic curve with respect to time in the experiment. This plotter can be operated by an input as low as 0.5 millivolt per inch with an input resistance of 200,000 ohms full scale. Accuracy is better than 0.2% of full scale with 0.1% repeatability on all ranges.

Time base accuracy is better than 5% of full scale and linearity better than 3%. Therefore, even when voltage is as low as a few millivolts when measuring the foam conductivity, the X-Y plotter still works properly. A simple sketch of this instrument is shown in Figure 9b.

### Foaming Agents

Three kinds of foaming agents were studied in this experiment. Namely, these were Fomex, Fomark CD-587M and AG-foam. The former two agents were manufactured by Colloidal Product Corporation, California and the AG-foam was made by Hayward Chemical Co., Kansas.

Both Fomex and AG-foam have already been marketed for herbicidal uses, but Fomark CD-587M was found harmful to plants under some conditions. All these three foaming agents were water soluble but showed some kind of chemical reaction with the drinking water (possibly due to the presence of chlorine

in water).

All the three agents possessed transparent colors: yellow in Fomex, purple in AG-foam, and pink in Fomark CD-587M, with different irritating orders. According to instructions, the gradient of diluting with water varied from 0.5% to 1%, or 2 quarts to 4 quarts per 100 gals of water. However, in this experiment, 0.25%, 0.5% and 1% were adopted.

No stabilizer or gel was added to increase the lifetime of foam in these experiments since the drainage may be desirable for the insect-killing effect. Therefore, foams produced in this experiment in general displayed the fast-draining properties.

#### Insecticide

Furadan 4 Flowable, manufactured by Niagara Chemical Division Co., New York, was the only insecticide applied in this experiment. It consisted of active ingredient 43.8% (Carbofuran) and 56.2% inert ingredient.

Furadan 4 Flowable was chosen for the corn borer control because it had a long residual life against the larvae. The manufacturer recommended  $\frac{1}{2}$  to 2 pints per acre, depending on the cut-off time for harvest. For ground spray rate of 10 gals per acre, 1.25% to 5% solution was suggested. In this experiment, 0.3% and 0.6% of Furadan 4 Flowable in the foaming solution were considered.

## INVESTIGATION AND PROCEDURE

Table 2. Parameters investigated during the experiment

Parameters	Levels
Air flow rate (cfm)	1.6, 3.1, 4.1, 6.0, 7.3
Liquid pressure (psi)	30, 40, 60, 70, 80
Percentage of foaming agents	0.2, 0.25, 0.5, 1.0

Three parameters that might affect the foam characteristics were considered in this experiment. Table 2 shows all of these three variables and their levels of interests. Levels listed here, however, were not all treated in each experiment. Particular interests of the tests were focused on the foams that were generated from the Fomex foaming solution.

Measurements of the foam properties such as the drainage rate and conductivity, the liquid pressure was generally set at 40 psi to meet the actual field condition. However, pressure at 60 psi was sometimes used for the convenience of comparisons.

Air flow rates, on the other hand, were expressed in terms of water level in the manometer during experiments, but it was converted into the actual unit, cubic feet per minute, by means of Figure 5 when data were processed. Lower levels of the air flow rate were always omitted as the lower percentage of foaming agents was used, for in that case it failed to produce desirable foams.

## Expansion Ratio

In the classical literature, the foam expansion ratio,  $E$ , was defined as a ratio of volume of foam generated to that of the foaming solution from which the foam was produced. The expansion ratio can also approximately be expressed as a reciprocal of specific gravity of foam itself, provided that the density of the foaming solution is the same as that of the pure water, or 1.94 slugs/ft<sup>3</sup>. Mathematical expressions for the foam expansion ratio follow:

$$\begin{aligned}
 \text{Expansion ratio } (E) &= \frac{\text{Specific weight of solution}}{\text{Specific weight of foam } (S_f)} \\
 &\approx \frac{62.4}{S_f} = \frac{1}{S_f/62.4} \\
 &= \frac{1}{\text{Specific gravity of foam } (S_{pf})} \\
 &\quad (14)
 \end{aligned}$$

Where the unit of the specific weight of foam,  $S_f$ , is in lb/ft<sup>3</sup> and the specific gravity of foam, the same as the foam density in the c.g.s. system, can be obtained by measuring the weight of a known-volume container with foam bubbles filled.

Therefore,

$$S_f = \frac{W_f - W_o}{V_c} \quad (15)$$

Where  $W_f$  = weight of container with foam, lbs.

$W_o$  = weight of container without foam, lbs.

$V_c$  = volume of container, ft<sup>3</sup>.



Procedures of measuring the weights of container and foam bubbles were done as the following steps:

a. Empty containers with a fine stream of water spray and then set them on the ground a few minutes for natural drying.

b. Weigh the containers before feeding foam bubbles, and obtain  $W_o$ .

c. Turn on the foam generator and feed the container.

d. As soon as the container is full, remove it and cut off the top part of the foam that is over-filled with a ruler.

e. Dry the outside wall of the container with cloth.

f. Weigh it again and obtain  $W_f$ .

Each sample of combination was taken at random within each replicate. There were three replicates adopted in measuring the foam expansion ratio.

#### Drainage Rate

A simple apparatus for the drainage-testing purpose is illustrated in Figure 8b. The foam drainage rate was then measured every twenty-five seconds immediately after the foam box, with fresh foam bubbles filled inside, was switched to the draining position (see Figure 8a). The drained liquid was then guided to a breaker that was sitting on a scale platform. Meanwhile, the weight of the liquid in the beaker was recorded manually. Using such apparatus, data should be taken with care because of the less sensitive response of the scale



when only a small amount of the drained water was added. A satisfactory practice in overcoming this difficulty was to slightly hit the beaker by a pencil before the data was recorded.

The foam that contained too much water always arose problems during the feeding process. It would drain very quickly before the box was full. This fast drained liquid, however, could not reach the beaker while the box was still in feeding position. To save this liquid for accurate recording, the foam box was tilted by a small angle while this watery foam was collected and later the box was leveled as usual position again as soon as it was swung back to the draining position. Foam with low fluidity, on the contrary, did not have such a problem, but the air-trapping became significant and needed some attention to keep errors low.

To express the foam drainage mathematically, equation 5 is considered:

$$V = V_0 (1 - e^{-kt}) \quad (16)$$

Accordingly, the drainage rate,  $Q$ , will simply be a differential form of the above equation.

$$\begin{aligned} Q = \frac{dV}{dt} &= k V_0 e^{-kt} \\ &= k (V_0 - V) \end{aligned} \quad (17)$$

Obviously equation 17 acts as a decreasing function. It will explain the watery foam with an appreciable accuracy, but, unfortunately, it fails to function quite well when the foams

with less water, or, the so-called "dry" foams are encountered. The drainage rate of this sort of foam usually follows a skewed bell-shaped curve with respect to time. Little is known about a curve which will fit these particular data. It seems that a regression analysis is the best way to solve this problem.

### Drainage and Expansion Ratio

Generally speaking, the expansion ratio of foams will increase as the liquid drained away from the foam bubbles. According to equation 15, with the same volume of foam, the liquid that drained will result in a decrease of the quantities,  $W_f$  and  $S_f$ . Consequently, the expansion ratio,  $E$ , will reciprocally increase. Suppose a container, with a volume  $V$ , is set to decay with time right after the foam bubbles are filled. Just as shown in Figure 10, at time  $t$  the volume of

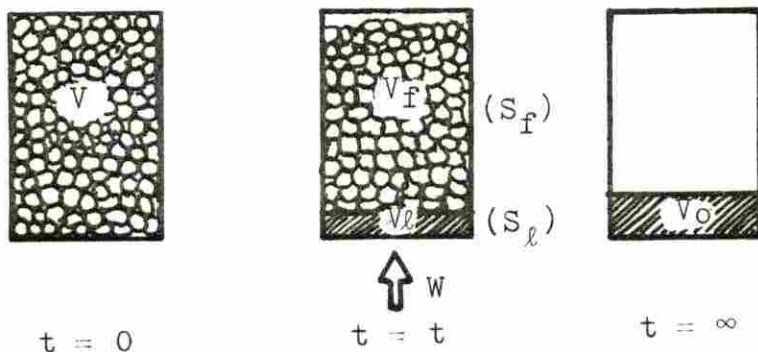


Figure 10. Foam decay and drainage in a container

foam will decrease gradually to  $V_f$  and the volume of the drained liquid will increase to  $V_\ell$ . Let  $S_f$  and  $S_\ell$  be the specific weight of foam and drained liquid respectively, and  $W$  be the total weight of foam and liquid in the container. According to the definition, the foam expansion ratio,  $E$ , is:

$$E = \frac{S_\ell}{S_f} \quad (18)$$

Here, the specific weight of liquid,  $S_f$ , does not change with time and presumably will keep constant at about 62.4 lbs/ft<sup>3</sup>.

On the other hand, the net weight of foam and liquid in the container can be expressed as:

$$W = V_f \cdot S_f + V_\ell \cdot S_\ell \approx V_o \cdot S_\ell \quad (19a)$$

Where  $V_o$  is the total volume of the drained liquid, or the volume of the drained liquid when  $t$  approaches infinite. Rearrange the above equation, then

$$S_f \cdot V_f = (V_o - V_\ell) \cdot S_\ell \quad (19b)$$

Combine equation 18 and 19b, the expansion ratio becomes:

$$E = \frac{S_\ell}{S_f} = \frac{V_f}{V_o - V_\ell} \quad (20)$$

When  $t = 0$  and  $V_\ell = 0$ , equation 20 is then in agreement with equation 14. But when  $V_\ell = V_o$  the value of the expansion ratio will become infinite. In the actual case, however, this is not true because as  $V_\ell$  approaches  $V_o$ , foam breakage will

occur during this long period, which will keep the expansion ratio from becoming infinite.

It has been fairly well established that  $V_\ell$  and  $V_o$  will obey such a relationship as:

$$V_\ell = V_o \phi(t) \quad (21)$$

Where  $\phi(t)$  is a time function. Also, suppose the volume of foam,  $V_f$ , decreases linearly with respect to the time  $t$  when the foam bubbles are decaying from the original volume  $V$ , therefore,

$$V_f = V ( 1 - bt ) \quad (22)$$

Where  $b$  is a constant. Apparently it will approach zero if the foam with less water is under testing.

To simplify equation 20, both equations 21 and 22 are substituted in and, meanwhile, remember the initial expansion ratio,  $E_o$ , is a ratio of  $V$  and  $V_o$ :

$$E = \frac{V ( 1 - bt )}{V_o ( 1 - \phi(t) )} = E_o \left( \frac{1 - bt}{1 - \phi(t)} \right) \quad (23a)$$

Suppose  $t$  is less than five minutes, the constant  $b$  will be nearly zero. The final result of equation 23 therefore becomes:

$$E = \frac{E_o}{1 - \phi(t)} \quad (23b)$$

## Conductivity of Foam

The conductivity of foam was measured by inserting a circuit between two plates either in the foam box or in the V-shaped chamber of the foam generator. In the former case it was to measure the conductivity of the static foam when the foam bubbles were decaying; while the latter, it was to measure that of the dynamic foam when the foam bubbles were being generated. A complete circuit is shown in Figure 11. Two 1.5 volt batteries in series were inserted in the circuit to supply a constant voltage. A small value of resistor was connected to provide a voltage for the input of the X-Y plotter. The voltage measured by the X-Y plotter will then be proportional to the current in the circuit.

$$I = \frac{e_{in}}{R_r} \quad (24a)$$

Suppose the resistance across the two plates is  $R_f$ . The voltage across the foam box is then  $e_t - e_{in}$  volts and the current,  $I$ , will be

$$I = \frac{e_t - e_{in}}{R_f} = \frac{e_{in}}{R_f} \quad (24b)$$

By arranging  $e_{in}$  to the left side of the equation, then

$$\begin{aligned} e_{in} &= \left( \frac{R_r}{R_f + R_r} \right) e_t \\ &= \left( \frac{1}{\frac{R_f}{R_r} + 1} \right) e_t \end{aligned} \quad (25)$$



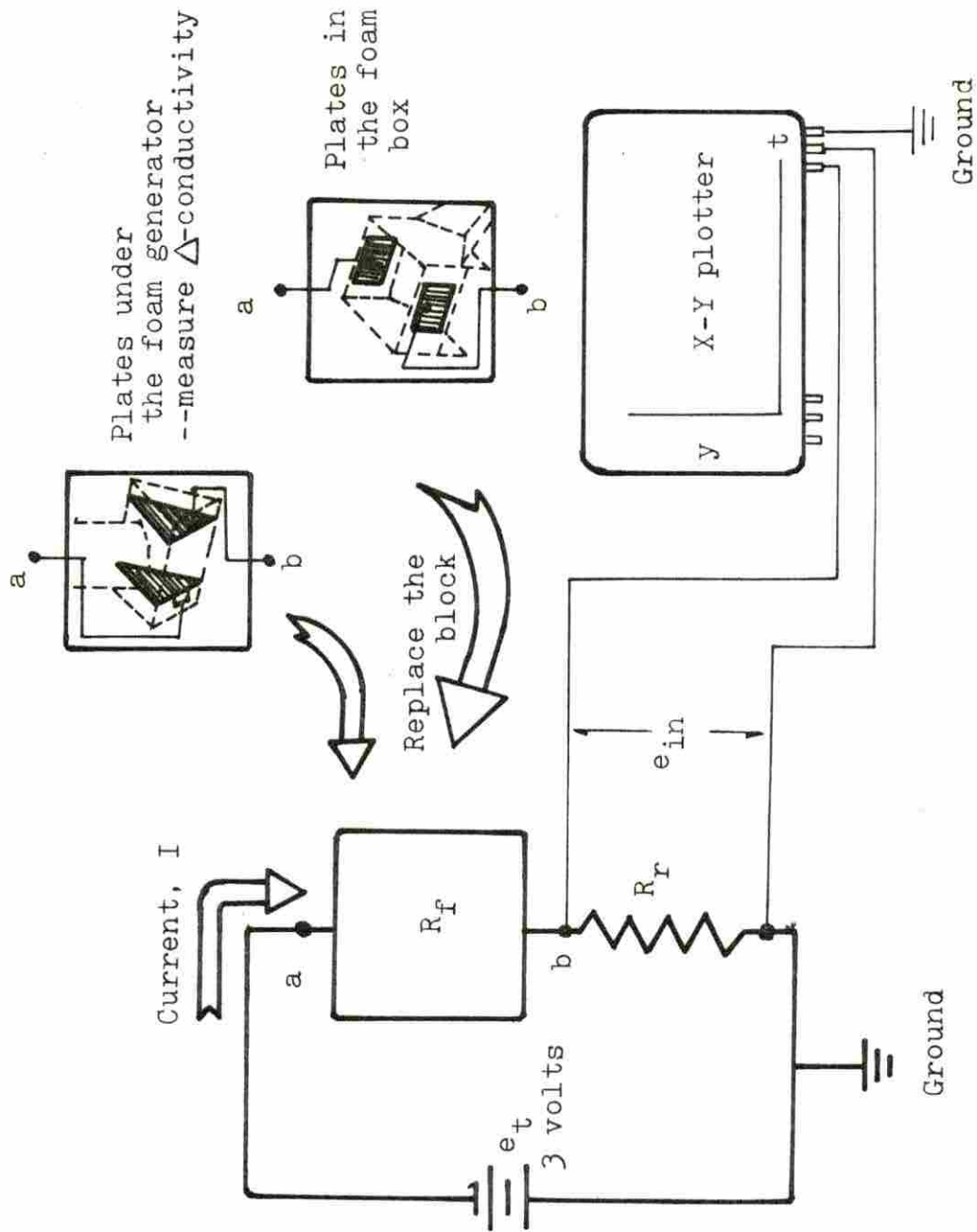


Figure 11. A complete circuit for measuring the foam conductivity

In the actual situation,  $R_r = 250$  ohms and  $e_{in}$  would be less than 50 millivolts. The current in the circuit is then less than 0.02 milliamperes and the resistance,  $R_f$ , will be greater than  $1.5 \times 10^5$  ohms. Under these conditions, the ratio  $R_f/R_r$  will be very much greater than 1. The input voltage,  $e_{in}$ , then can be approximately expressed as an inverse of the foam resistance,  $R_f$ :

$$e_{in} \approx \left( \frac{R_r}{R_f} \right) e_t = \frac{750}{R_f} \quad (26)$$

The conductance of foam across the foam box can be defined as:

$$G = \frac{\sigma A}{L} \quad (27)$$

Where  $\sigma$  = foam conductivity,  $\text{ohm}^{-1}\text{cm}^{-1}$ .

$G$  = foam conductance,  $\text{ohm}^{-1}$ .

$A$  = cross section area of the foam box,  $\text{cm}^2$ .

$L$  = length of the foam box, cm.

Actually the conductance,  $G$ , is a reciprocal of the resistance,  $R_f$ . Thus, suppose  $\epsilon = A/L$  and then combine equation 26,

$$\sigma = \frac{e_{in}}{750 \epsilon} = k' e_{in} \quad (28)$$

Where the units of  $\sigma$  and  $\epsilon$  are  $(\text{ohm-cm})^{-1}$  and cm respectively and  $k'$  is another constant. In other words, the voltage the X-Y plotter reads in and plots out is proportional to the conductivity of the foam bubbles between those two plates.

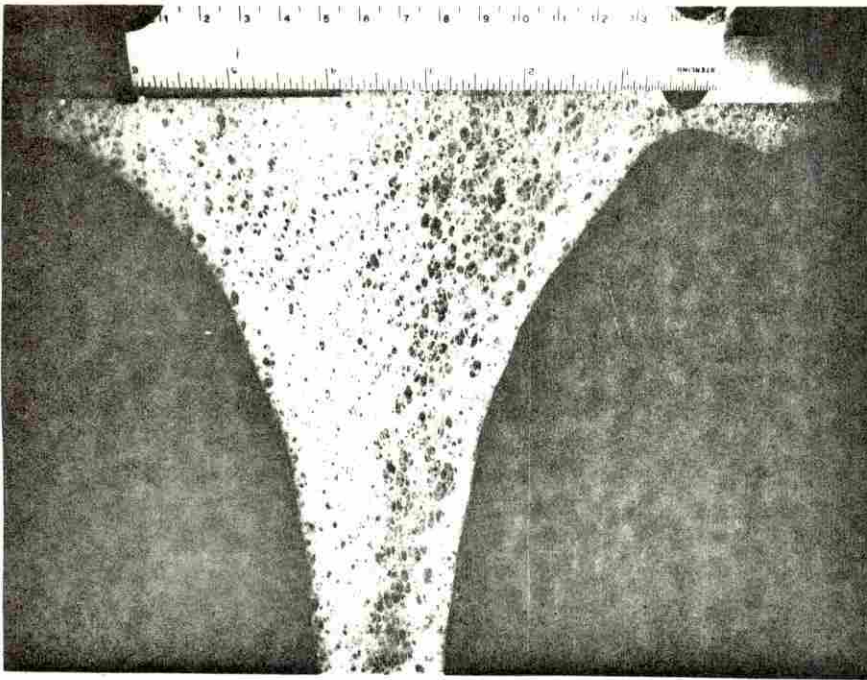
## Foam Classification

Purpose of classifications of foam was to recognize how and what parameters can be controlled efficiently in order to get the desired quality of foam. The concept of this experiment was based on the shape and bubble size of foam when it was running through the slit opening under the foam generator.

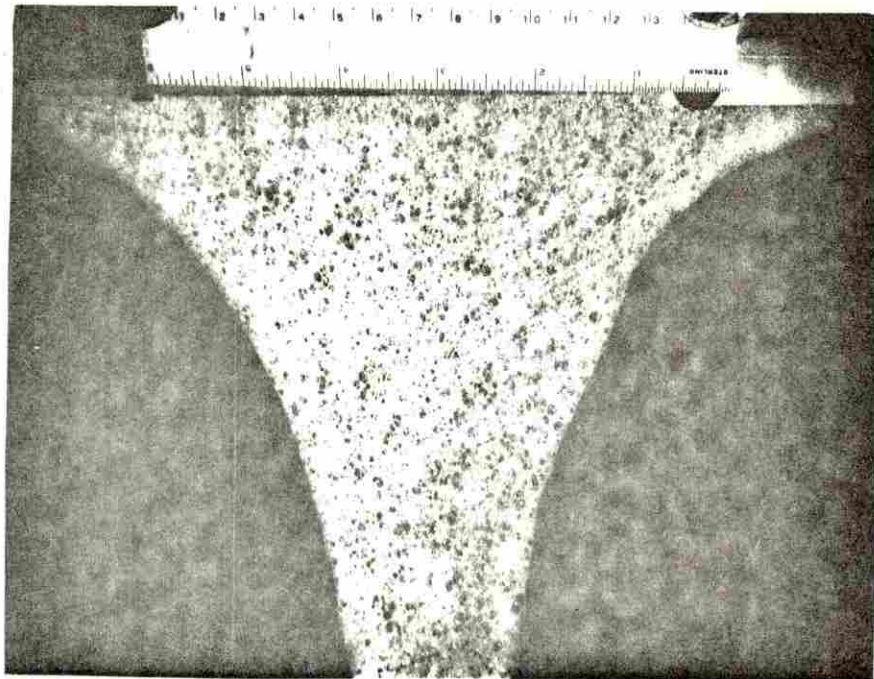
According to experience, foams did appear to undergo several different states when dropping. Some flowed continuously and smoothly through the whole foam column but some started to break apart. Reasons for this breakage might be due to different situations of balance of the gravitation force and the foam consistency itself.

In determining the shape and curve of the foam column, a polaroid camera was employed. Because the bubbles were moving very fast, a camera flash was required. The liquid pressure was kept at a constant rate of 40 psi, and only the Fomex foaming agent was tested with percentage levels at 1.00, 0.50, and 0.25%.

Before starting the experiment, a series of pictures for 1% Fomex was taken first by adjusting the air flow rate. Among these pictures, six typical ones were chosen for latter references and each was assigned an index number respectively. These pictures are shown on Figures 12, 13 and 14. As we can see, the bubble distribution will appear more even and the curve will gradually become straight with an increase of the



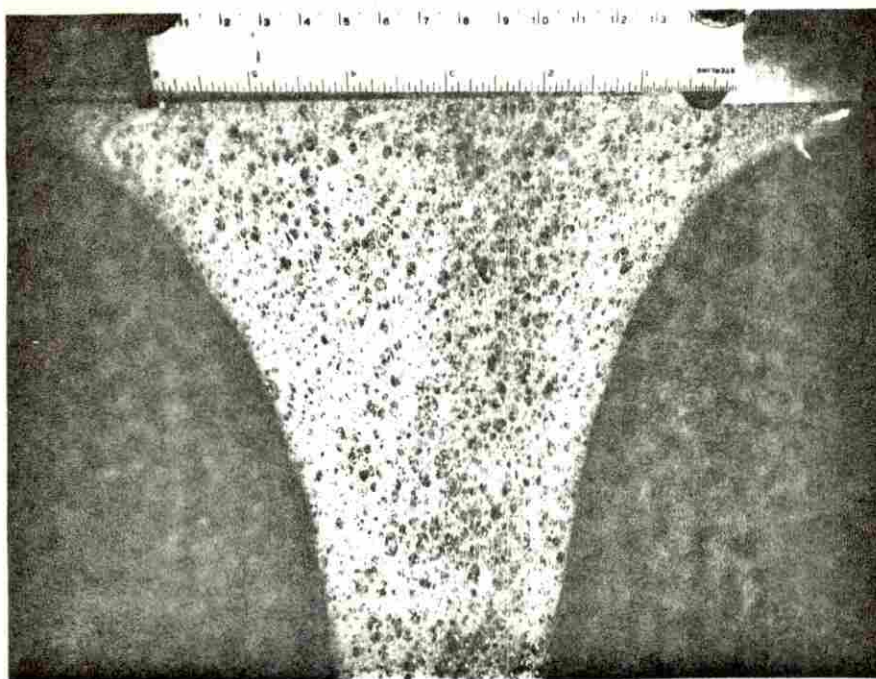
(a).  $N = 1$



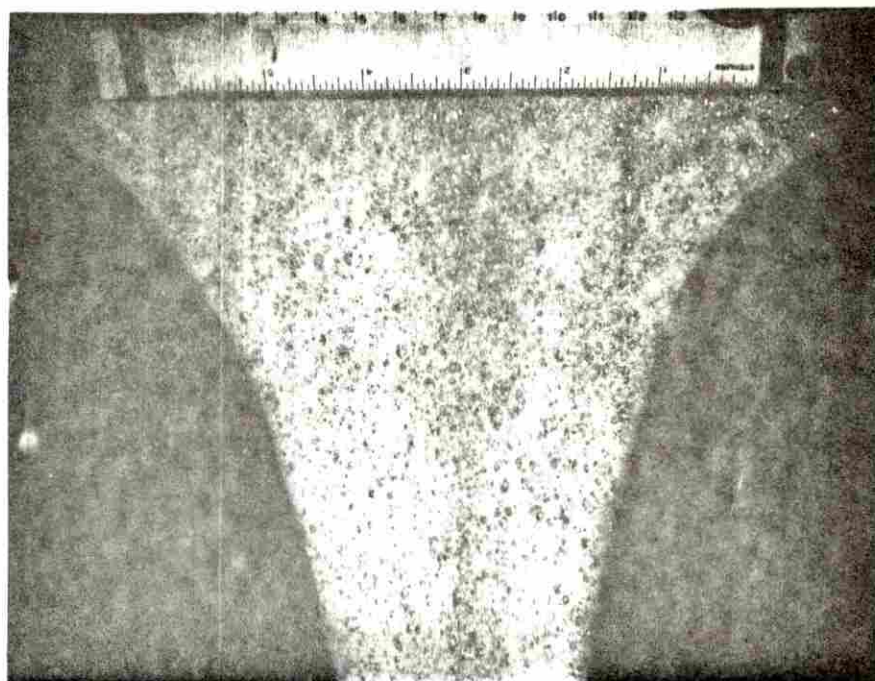
(b).  
 $N = 2$

Figure 12. Pictures of foam column with index number





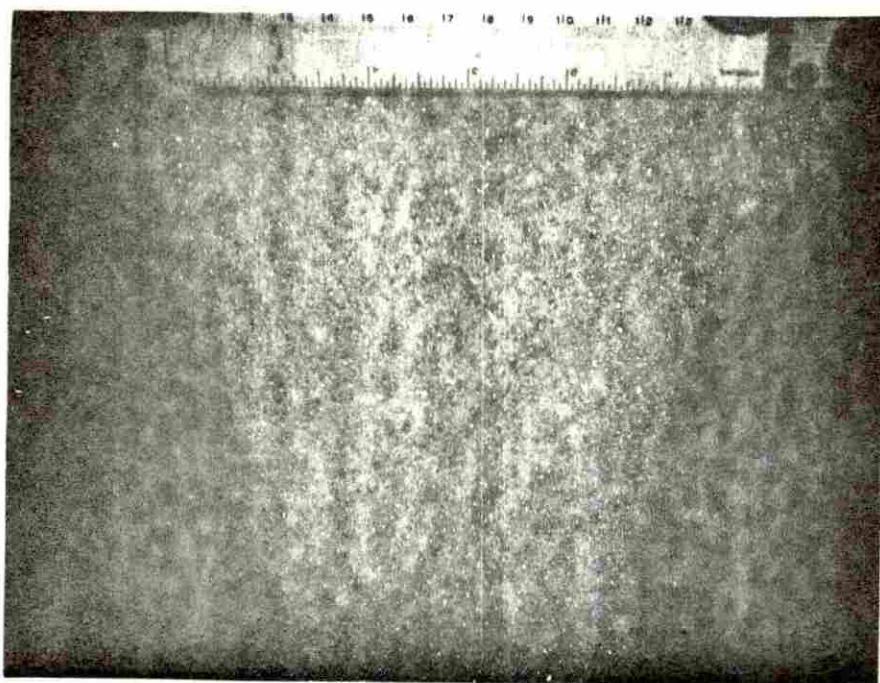
(c).  
N = 3



(d).  
N = 4

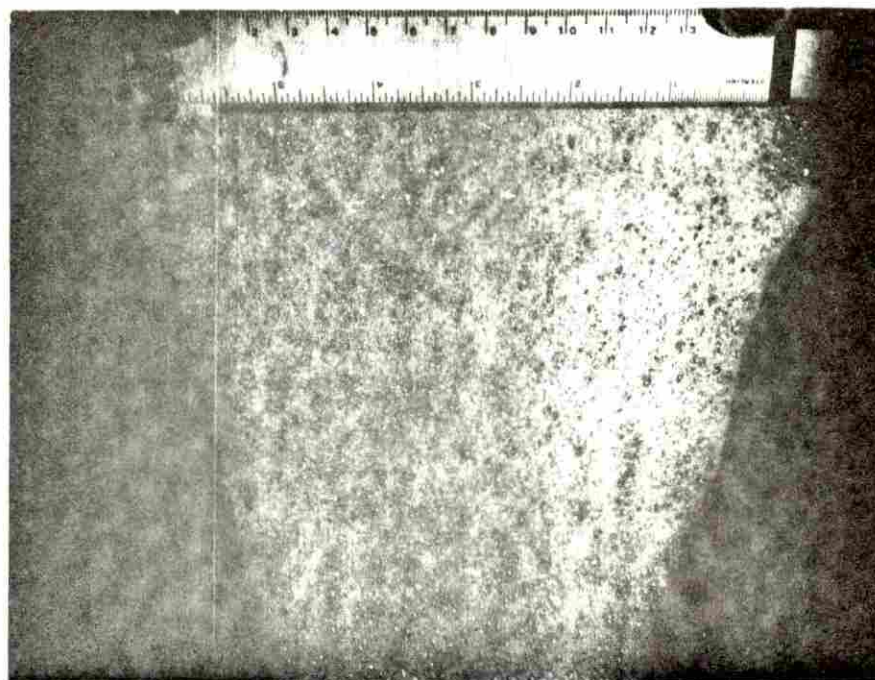
Figure 13. Pictures of foam column with index number





(e).

$N = 5$



(f).

$N = 6$

Figure 14. Pictures of foam column with index number

foam index number,  $N$ .

To materialize these index numbers, an attempt is made here to outline an equation from the pictures taken. By noting Figure 15, one will see that the dimensions of the foam column can simply be expressed as two ratios  $\alpha$  and  $\beta$ . Here,  $\alpha$  indicates the height of foam dropping and  $\beta$ , the ratio that the foam column contracts, or the ratio of the width of the foam column. To simplify the case,  $\alpha$  was set at  $\frac{1}{2}$  and  $\frac{1}{4}$ . By measuring  $\beta$  from each picture, two equations can be approximately stated as follow:

$$\text{For } \alpha = \frac{1}{2}: N = 17.644 \beta - 0.917 \quad R^2 = 0.9679 \quad (29a)$$

$$\text{For } \alpha = \frac{1}{4}: N = 17.533 \beta - 2.841 \quad R^2 = 0.9788 \quad (29b)$$

By using the above equations, the index number will be clearly defined. However, it is worthwhile to note that equations will be valid only in a range of  $N$  from 1 to 6.

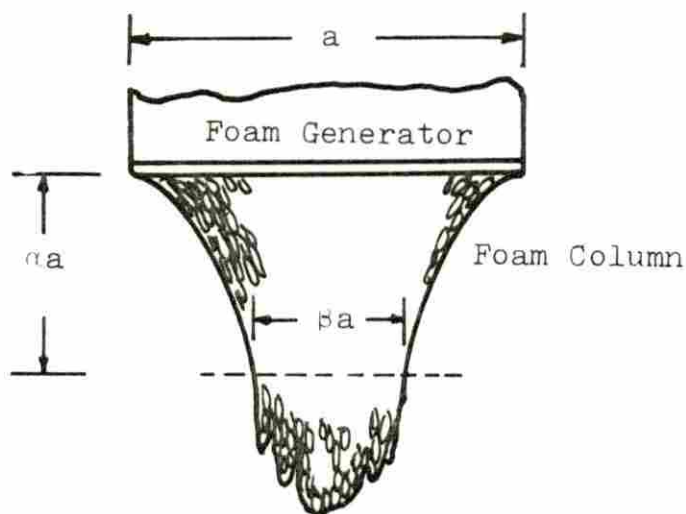


Figure 15. Two ratios,  $\alpha$  and  $\beta$ , which describe the dimensions of the foam column

During the experiment, the polaroid camera should be positioned at the same distance when the standardized pictures were taken. Thus, with shutter and lens wide open, the scale in the focal plane of camera will be similar to that of the pictures. To compare the picture and the image in the camera, one of those six standardized foam pictures was first randomly chosen. Air flow rates were then adjusted until the similar shape of both resulted. The criterion of shape similarity was examined by naked eye or simply by taking another picture if necessary and comparing them afterwards.

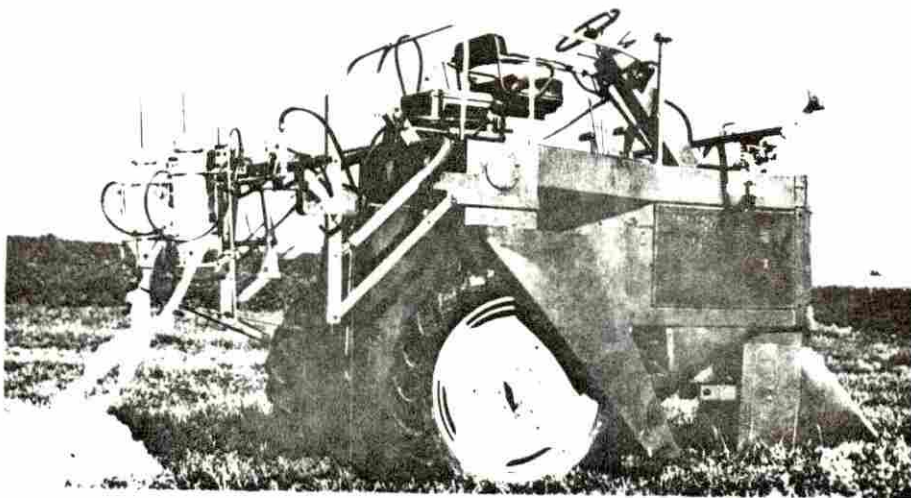
Each treatment (index number) had three replicates in three different percentages of Fomex, namely, 1.00%, 0.50% and 0.25%. Another comparison with additions of 0.3% and 0.6% of the insecticide, Furadan 4 Flowable, was also performed.

### Field Study

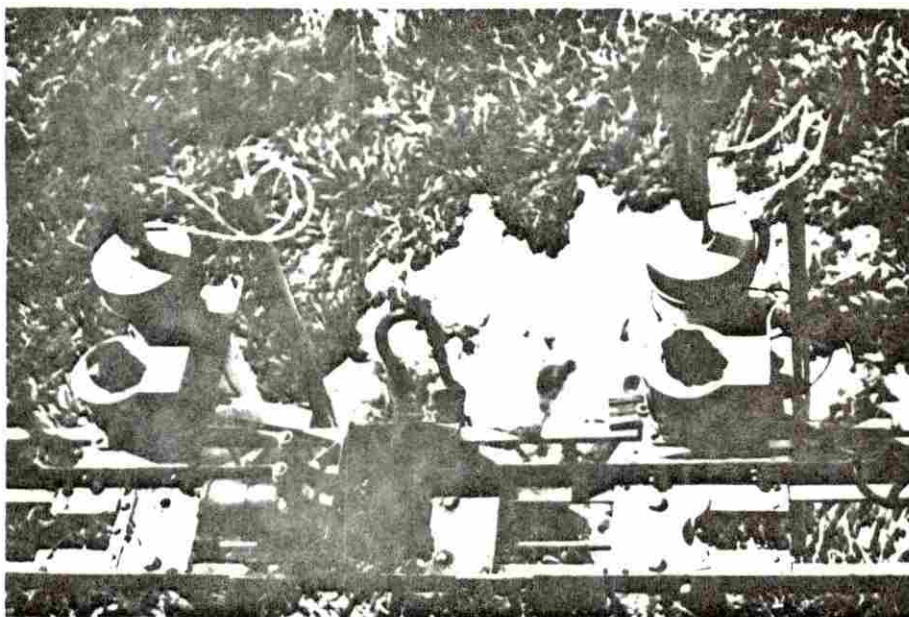
Foams of Fomex foaming agent were used as an insecticidal carrier of Furadan 4 Flowable for corn borer control. Three types of foam, medium (A), dry (B), and wet (C) types, and two sizes of nozzle, 10 and 20 gals per acre, and two percentages of foaming agent, 0.25% and 0.5% were applied during this experiment.

There were two similar foam generators mounted on a John Deere high clearance tractor (as shown on Figure 16). Each foam generator has an autotransformer attached in order to





(a). Sideview of the foam generator on tractor



(b). Top view of the foam generators on tractor

Figure 16. General view of the foam generators mounted on a John Deere high-clearance tractor

control the air flow rate. A generator attached on the top front of the tractor supplied the voltage for fan motors.

During the experiment, a random process was employed within each of four blocks. Each type of foam had four treatments, in which the sizes of nozzle and the percentages of foaming agent were nested in a factorial arrangement. Another four treatments were designed for spraying and three check plots were used.

Types of foam were classified by the expansion ratio. The expansion ratio was set at 30-35 for the medium (or, type A) foam, more than 100 for the dry (or, type B) foam and 20 for the wet (or, type C) foam.



## RESULTS AND DISCUSSIONS

## Notations

Listed here are some notations that will be used throughout these discussions:

$A_f, A_w$  = air flow rate, cfm. and in. of water in the manometer.

AG = AG-foam foaming agent.

AO = AG-foams without addition of insecticide.

ANOVA = analysis of variance.

$C_i, K_i$  = constants,  $i = 1, 2, 3, \dots$

E = expansion ratio, dimensionless.

FK = Fomark foaming agent.

FM = Fomex foaming agent.

FO = Fomex foams without insecticide.

F4, F8 = Fomex foams with additions of Furadan 0.6% and 0.3%.

N = Foam index number, dimensionless.

$P_\ell$  = liquid pressure, psi.

Q = drained liquid, grams.

$S_f$  = specific weight of foam,  $\text{lb/ft}^3$ .

T, t = time, seconds.

$\alpha_f$  = percentages of foaming agent, %.

$\gamma_b$  = back pressure ratio.

$\sigma$  = foam conductivity measured from foam box, mv.

$\sigma_\Delta$  = foam conductivity measured from the discharge box, mv.

v = drainage rate, grams/25 seconds.

### Expansion Ratio

It has been fairly well established that the expansion ratio of foam depends to a large degree on the volume of air contained within foam bubbles. According to the definition of expansion ratio, the more air captured the higher expansion value will be obtained. Air thus becomes a prerequisite factor that affects the foam formation, or, in other words, the behavior of the foam expansion ratio. Without air running into the solution, no bubbles will then result.

However, a caution is worth noting in this regard. Previous knowledge has indicated that pure water does not foam. Thus a different kind of solution, or percentages of foaming agent will give completely different results of expansion ratio. In actual operation, foaming agents act as cement and help water capture the incoming air. Generally speaking, the more foaming agent that exists in the solution the stronger the foam structure will likely be. Obviously, this strong bubble structure will withstand a quick collapse or tolerate an introduction of more air.

To determine the expansion ratio, three types of foaming agents, AG-foam, Fomark and Fomex were tested. The results are shown in Figure 17, 18, and 19 respectively. A preliminary investigation of these graphs indicates that both air flow rates and percentages of foaming agent are dominant factors in the response of the expansion ratio. At the same conditions,

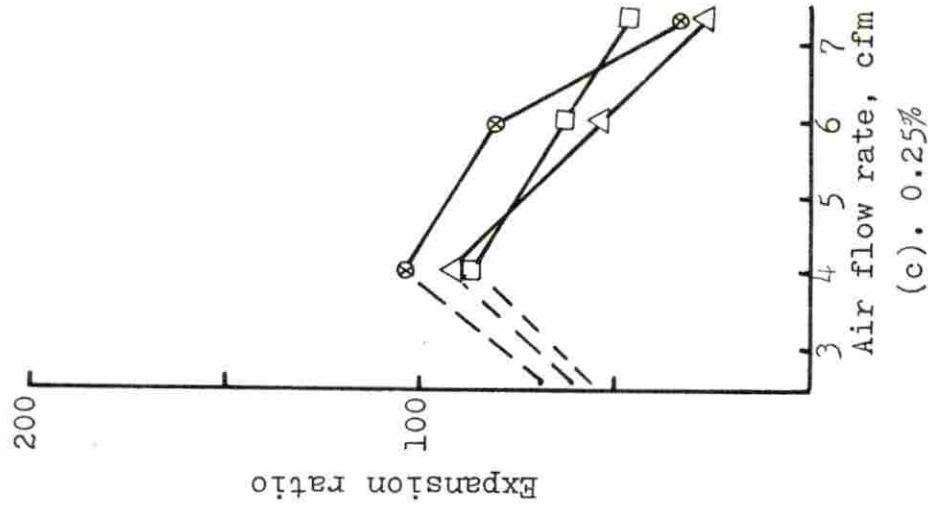
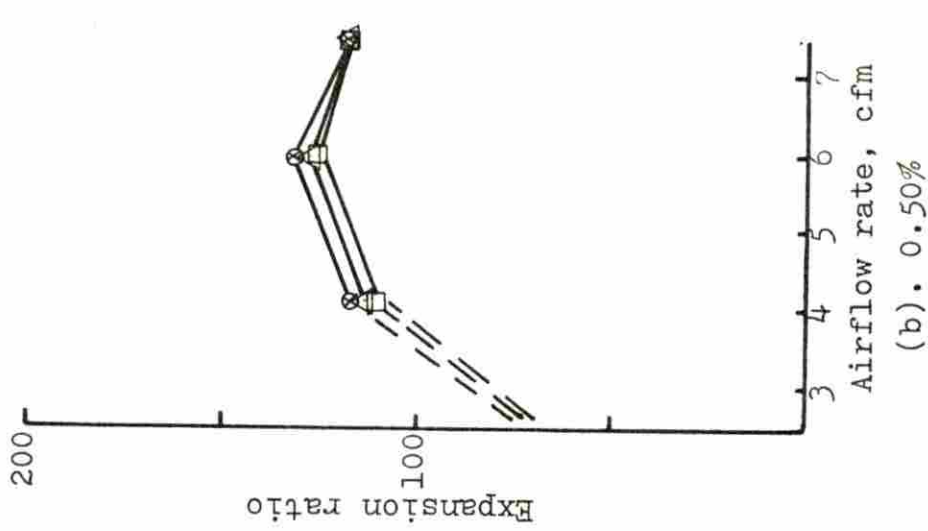
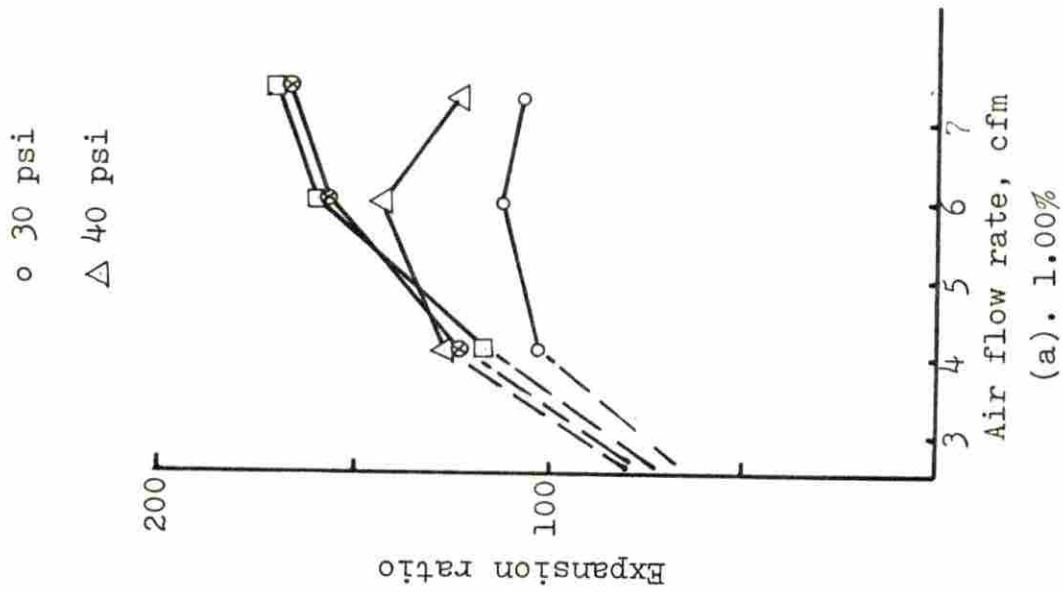


Figure 17. Expansion ratio of AG-foam

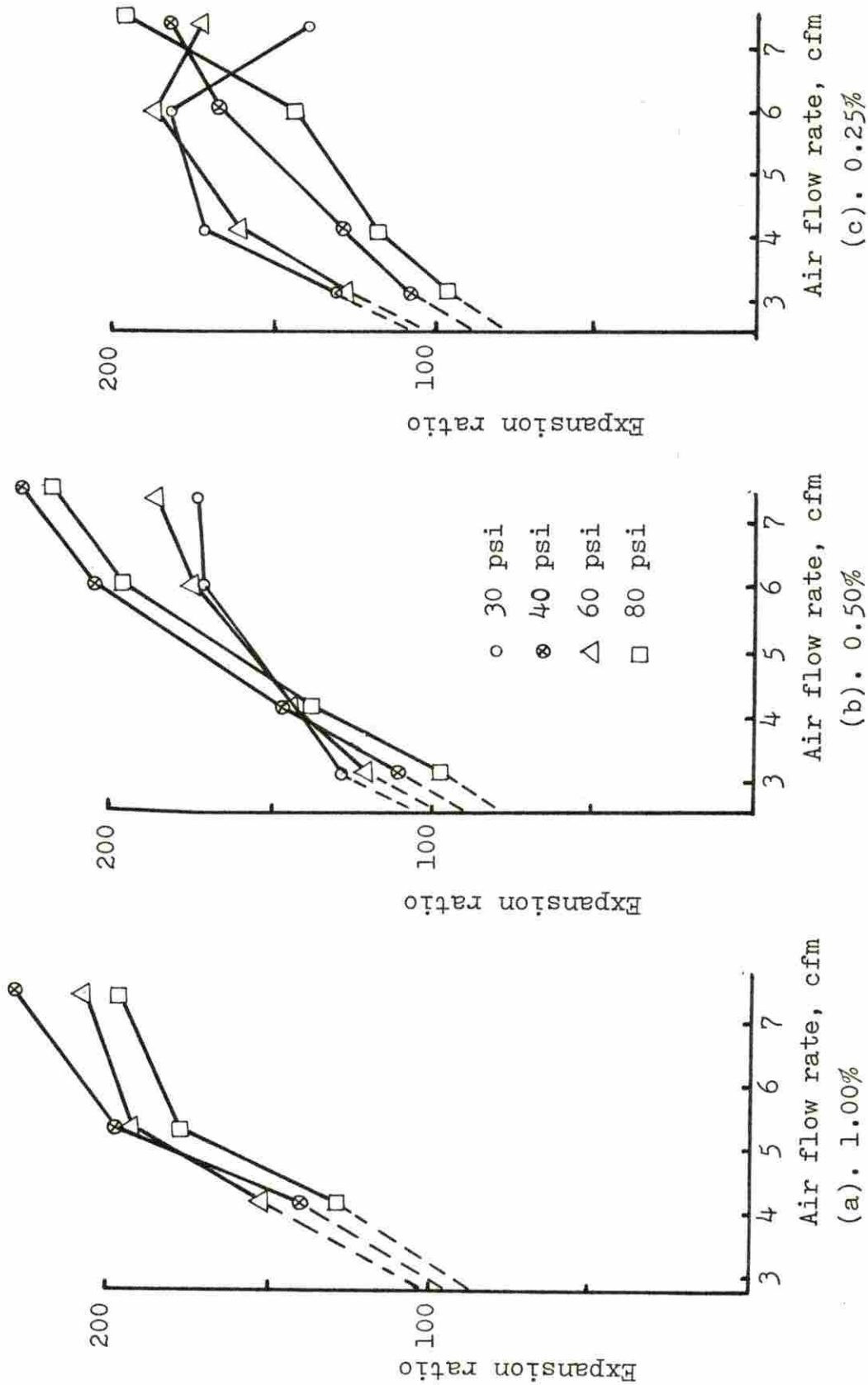


Figure 18. Expansion ratio of Fomark foam

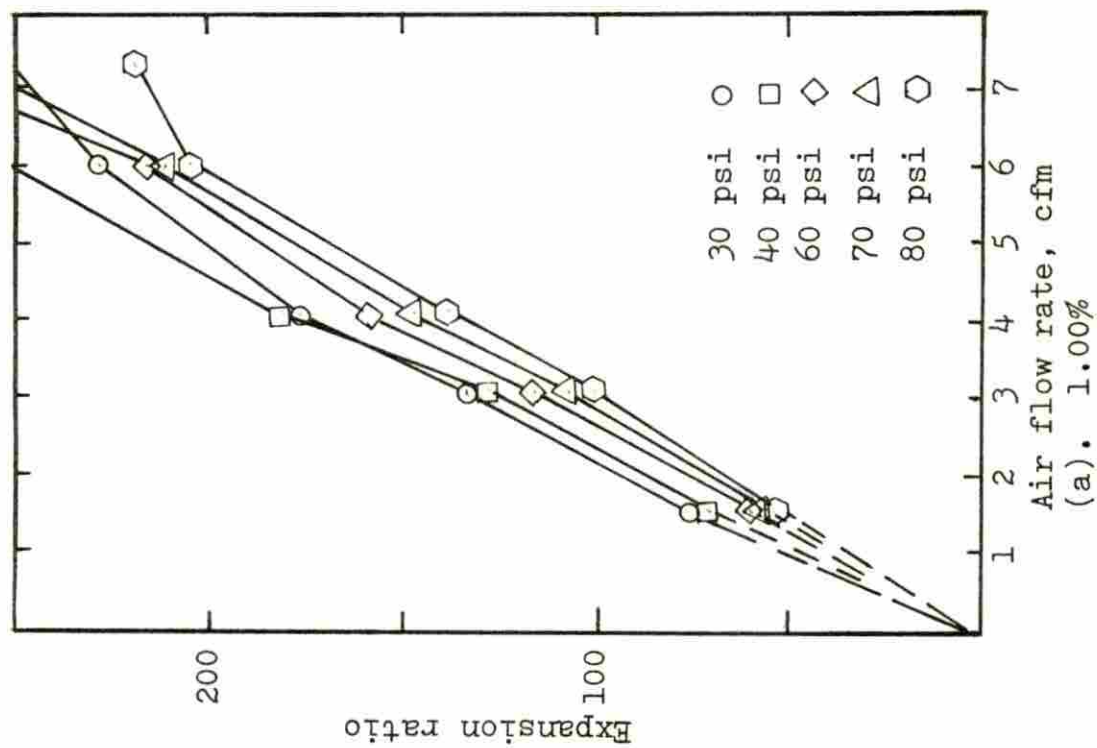
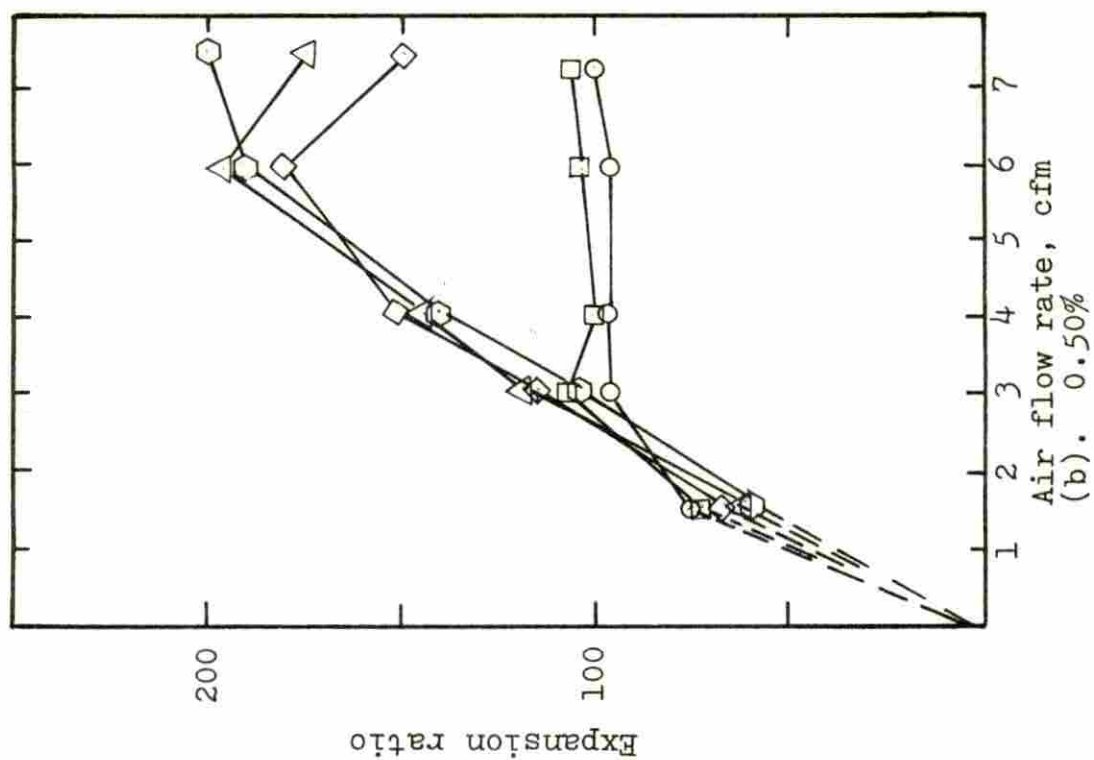


Figure 19.1. Expansion ratio of Fomex foam



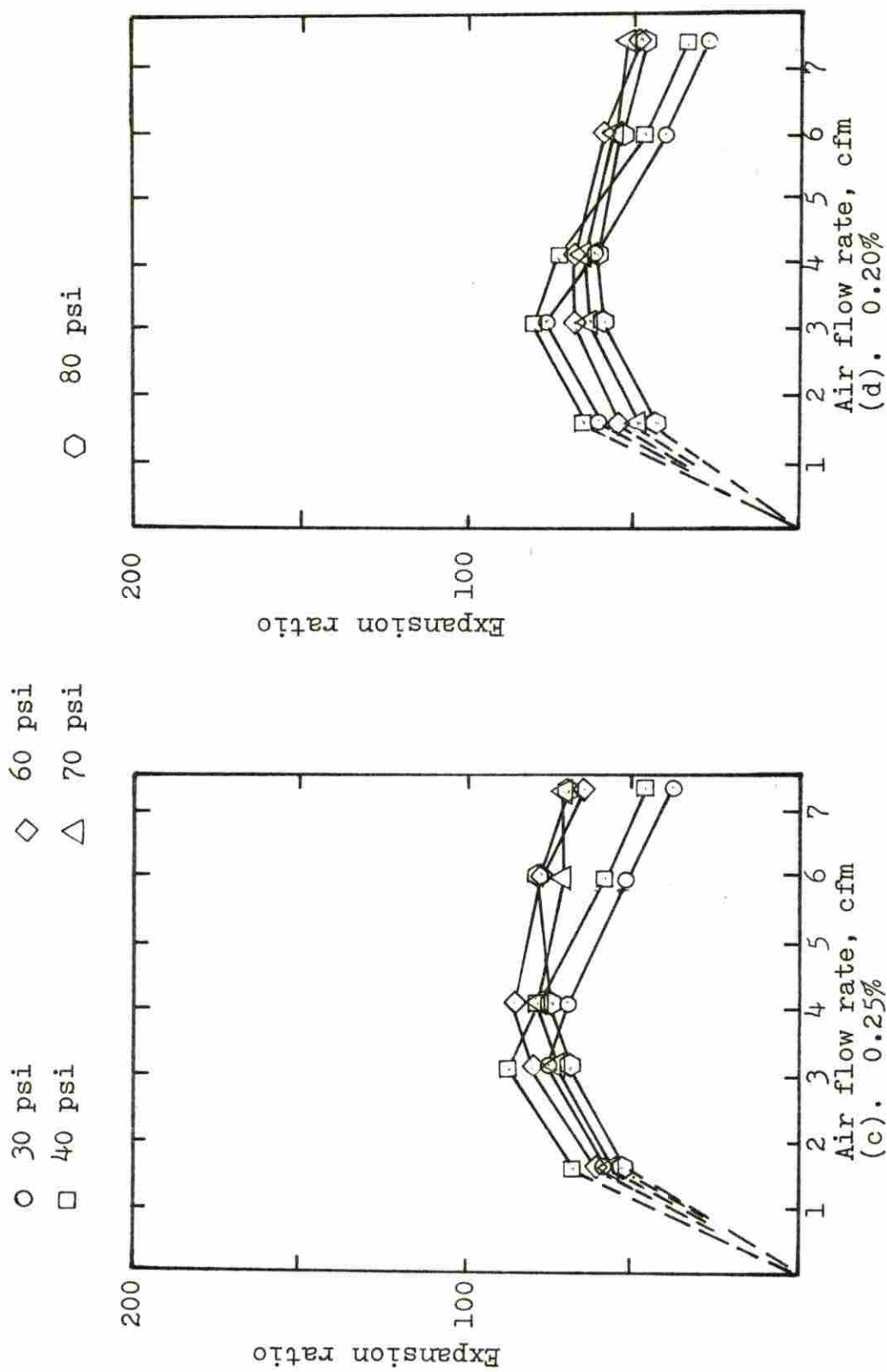


Figure 19.2. Expansion ratio of Fomex foam

however, AG-foam produced lower expansion ratio than the others did and it seems that Fomark produced higher expansion ratios throughout the whole percentage range of foaming agent even when it was as low as 0.25%.

Theoretically, there exists a minimum value of expansion ratio in each case. According to equation 14,

$$E = \frac{62.4}{S_f}$$

In this minimum situation,  $S_f = S_\ell = 62.4$ . Therefore,  $E = 1$ . The unit expansion ratio only occurs when air stops flowing completely and the solution should act ideally like pure water. Actually, this case will not happen because a small layer of icecream-like foam will generally result even without the fan motor running. Therefore, the minimum expansion ratio should be a small amount bigger than 1. The dash lines on these graphs show this tendency of approaching the unit expansion ratio.

Results of statistical analysis of variance for the Fomex foaming agent (see Figure 19.1 and 19.2) are shown on Table 3, in which effects of all variables and their combinations listed are very highly significant even as low as at the 0.05% confidence level.

Effects of Foaming Agents As mentioned before, foaming agents act like a kind of cement within the skeleton of foam. Therefore, more foaming agent added will then enhance the potential of foam bubbles in receiving more air and consequent-

Table 3. Analysis of variance for the foam expansion ratio of Fomex foams

Mean: 102.15 C.V.: 7.203%

Source of Variation	Degree of Freedom	Mean Square	F-Test
Replicates	2	195.833	--
Percentage of foaming agent (%)	3	188,054.535	3,473.817***
Liquid pressure ( $P_\ell$ )	4	1,673.065	30.906***
% x $P_\ell$	12	3,054.508	56.424***
Air flow rates ( $A_f$ )	4	43,383.170	801.390***
% x $A_f$	12	23,563.228	435.269***
$P_\ell$ x $A_f$	16	1,325.275	24.481***
% x $A_f$ x $P_\ell$	48	487.351	9.002***
Error	198	54.135	
Corrected total	299	3,744.177	

\*\*\* Significant difference at the 0.05% level.

ly increase the foam expansion ratio. This situation is obvious as shown in Figure 20, in which an overall effect of the percentage of foaming agent is indicated. An increase of the foaming agent will result in a steady increase of the expansion ratio. But one will see that as more foaming agent is added, the response of expansion gradually saturates and will not increase further. As a matter of fact, foams with higher expansion ratio are in a unstable state. Within bubbles, air was trying to escape due to its low density but the solution film, on the other hand, tries to hold the air down. These two

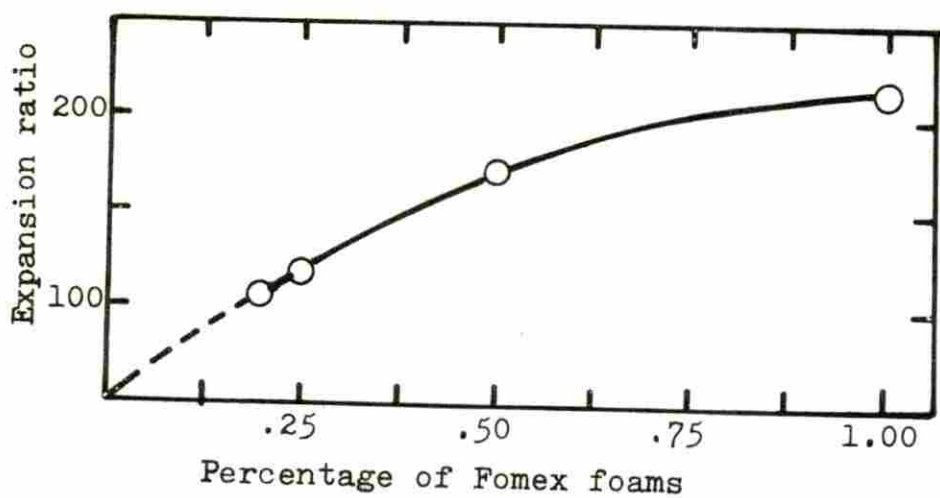


Figure 20. Effects of percentage of foaming agent on expansion ratio

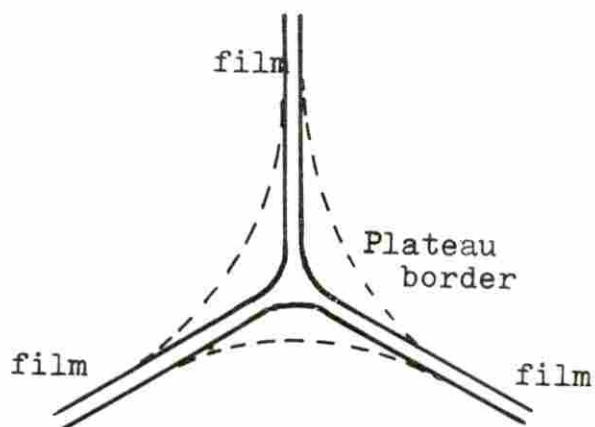


Figure 21. Three films meet together and form a Plateau border

forces are in equilibrium but the quantity will increase as more air is introduced. Thus, factors such as temperature, wind speed, etc., will become significant enough to break the bubbles down. The other possibility might be due to saturation of the solution.

Effect of the Air flow      The air flow rate is one of the most important factors that steadily and effectively control the foam expansion ratio. Less sufficient air supply generally resulted in the formation of foams with thicker bubble walls as well as greater Plateau border (Figure 21). Excess air, however, will cause thinning of bubble walls and eventually will easily break the bubbles down.

The overall effect of air flow rates on foam expansion is illustrated in Figure 22, in which effects of other factors are pooled together. Expansion ratio in Figure 22, however, exhibits the same characteristics as the foaming agent effects. There exists a maximum value of expansion ratio and after that, even more efforts are exerted the expansion ratio will not increase further. This ridge of expansion is shown in Figure 23 and Figure 24. Beyond these points on the curve, the expansion ratio will thus go down. It is interesting to note that the value of expansion ratio on the ridge tends to be higher when all three factors have a positive increase. Both sides of the ridge show the distinct types of foams when generated. As Figure 23 and Figure 24 show, foams on the side A of the curve characterized a kind of continuity, smoothness



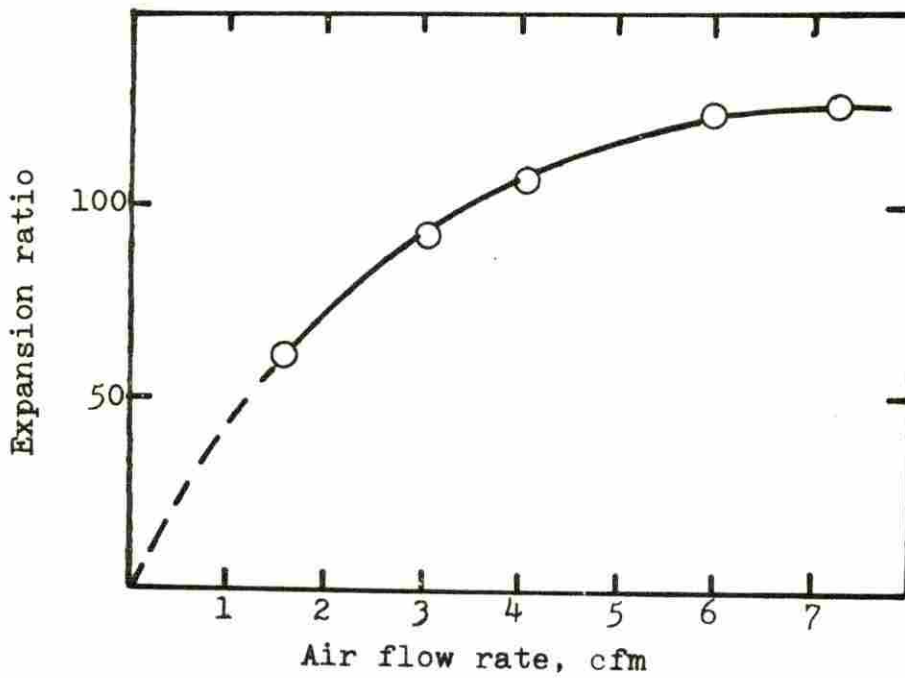


Figure 22. The overall effect of air flow rate on expansion ratio

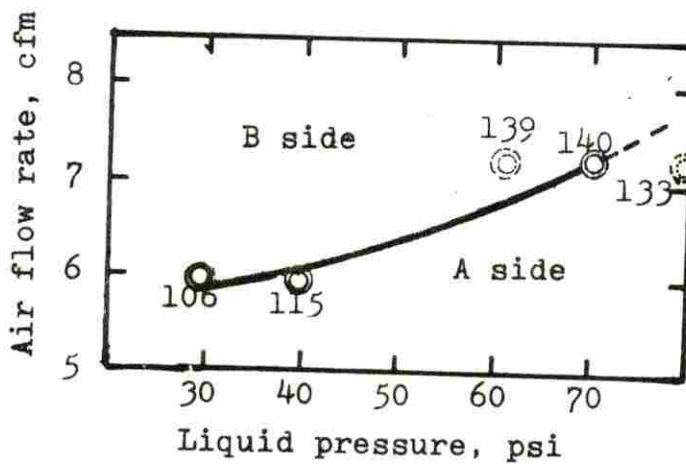


Figure 23. The maximum expansion ratio curve in a plane of air flow rate and liquid pressure. Number on the point is expansion ratio

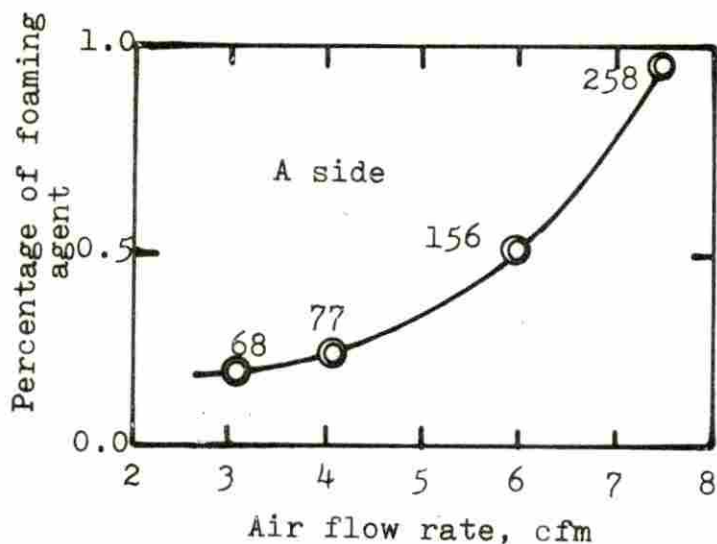


Figure 24. The maximum expansion curve in a plane of the air flow rate and the percentage of Fomex foaming agent. The number on the point is expansion ratio

and well-distributed bubble size, or a kind of "delicate" foam. Foams of the side B, on the contrary, displayed some unfavorable properties such as discontinuity, broken bubbles, less efficiency in capturing air, etc, or a kind of "harsh" foam.

This foam ridge phenomenon, however, is in quite close agreement with the Metzner and Brown's discovery (31) that, as they described, there existed two distinct regions, quiet and turbulent, in mass transfer of foam. The so-called quiet region will be identical to the side A of the expansion ridge; while the turbulent region will coincide the B side.

Interaction between air flow rates and percentages of foaming agent is another important source of variation (Table 3), in producing foams of different expansion ratios. Figure 25 manifests this effect. The expansion value changed not only

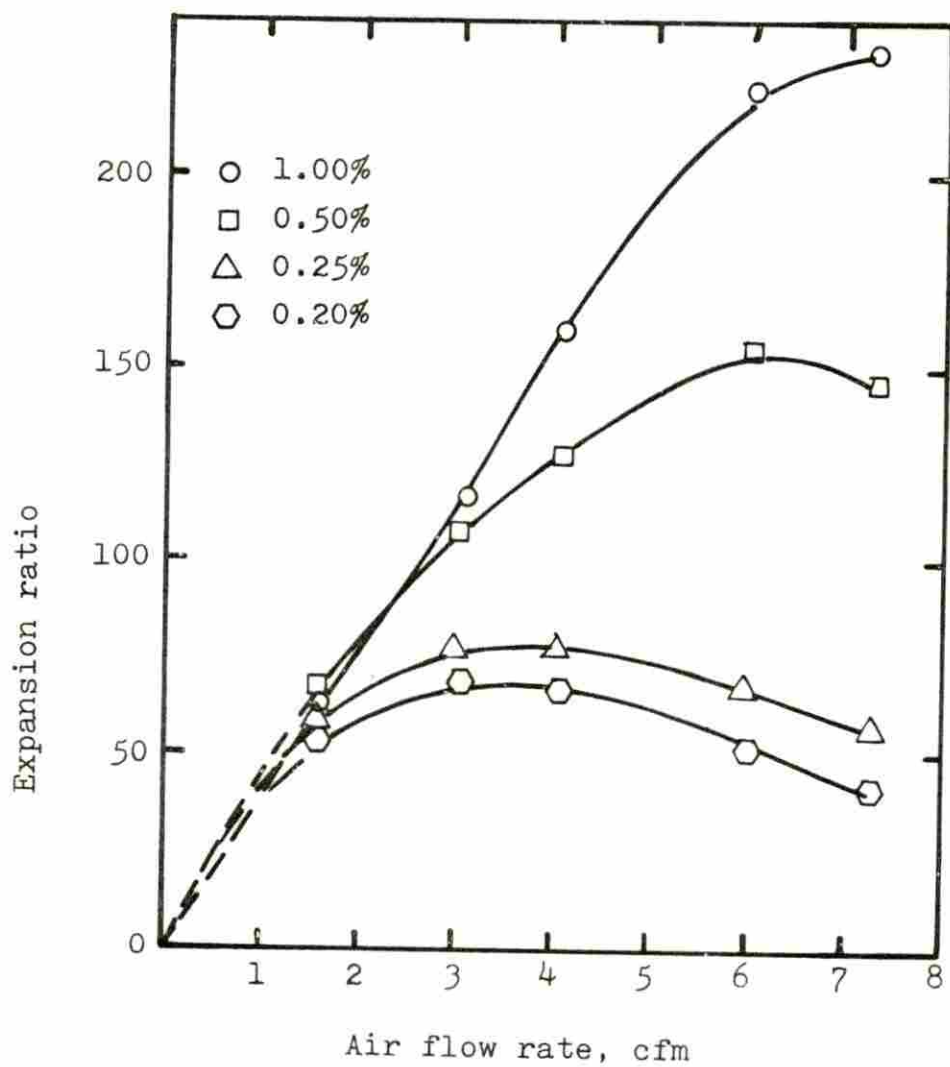


Figure 25. Effects of air flow rates and percentages of Fomex foaming agent on expansion ratio

due to the percentage of foaming agent but due to the air flow rate also. It is important to note that the position of maximum point also moved further once either one of these two factors changed.

#### Effects of Liquid Pressure

Generally speaking, variation of expansion ratio due to a change of liquid pressure did not appear so sensitive as the other variables did. By looking at the overall effect, it is obvious that response of the liquid pressure was nearly constant as shown in Figure 26. Nevertheless, this parabolic curve did set another example of the specific characteristics of the expansion ratio as just discussed.

Theoretically, an increase of liquid pressure will decrease the foam expansion ratio because the total weight increased. But, as Figure 26 indicated, it seems not quite true. Undoubtedly, there must have another factor coming into effect. However, it is important to remember that the distance between

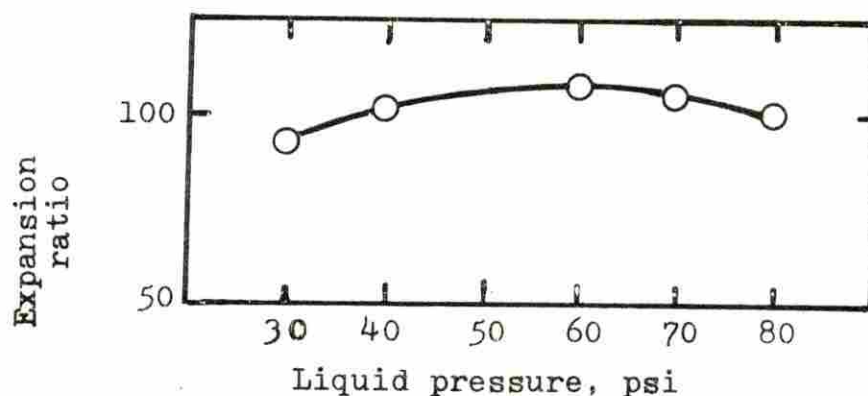


Figure 26. The overall effect of liquid pressure on expansion ratio (FM foams)

the nozzle and screens in the foam generator should be so arranged that all spraying particles can cover the whole screen area to keep higher production efficiency. But actually this condition could not be maintained most of time because the nozzle spray angle was a little pressure dependent, and the air capture efficiency thus suffered.

In spite of a little sacrifice in expansion ratio as liquid pressure increased, the quality of foam was improved. In fact, the generated foam would tend to be more continuous and smooth as well as more uniform distribution when pressure was increased. Foams on the side A in Figure 23 has shown this tendency. The interaction effects of liquid pressure with

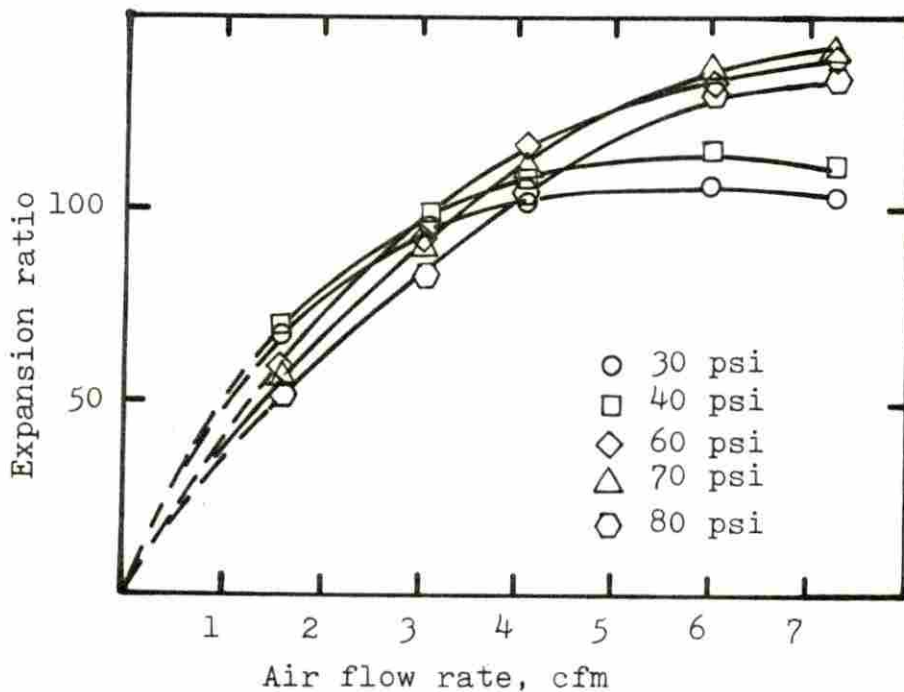


Figure 27. Interaction effects between air flow rates and liquid pressure on expansion ratio of FM foams



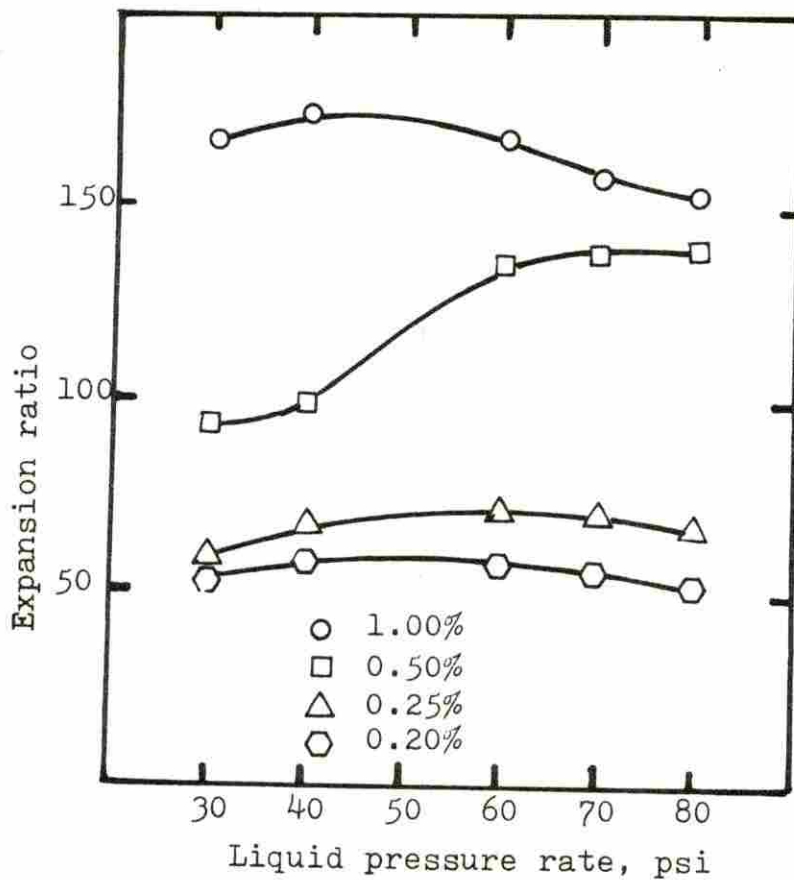


Figure 28. Interaction effects between the percentages of FM foaming agent and the liquid pressure

both air flow rates and percentages of foaming agent are shown on Figure 27 and Figure 28, in which the basic principle we discussed still follows although some deviations sometimes occur.

Effects of Insecticide To determine the effects of insecticide on the expansion ratio, 1% Fomex foaming agent was mixed with two percentages of Furadan, 0.3% and 0.6%, or the notations--F8 and F4 respectively. Figure 29 shows the final results when liquid pressure was kept constant at 40 psi; while Figure 30 shows the condition when the air flow rate was

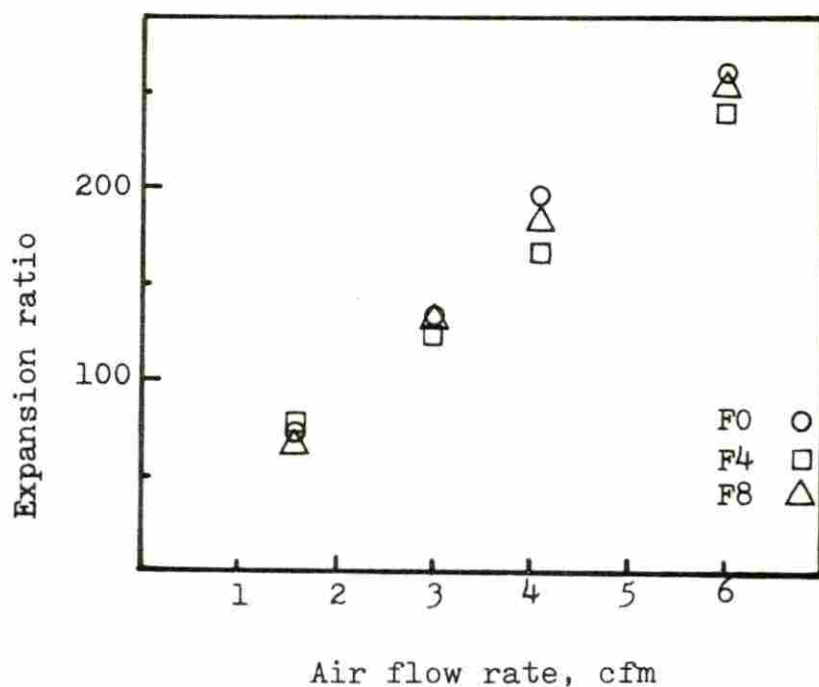


Figure 29. Effects of air flow rate on expansion ratio with addition of Furadan insecticide (liquid pressure at 40 psi)

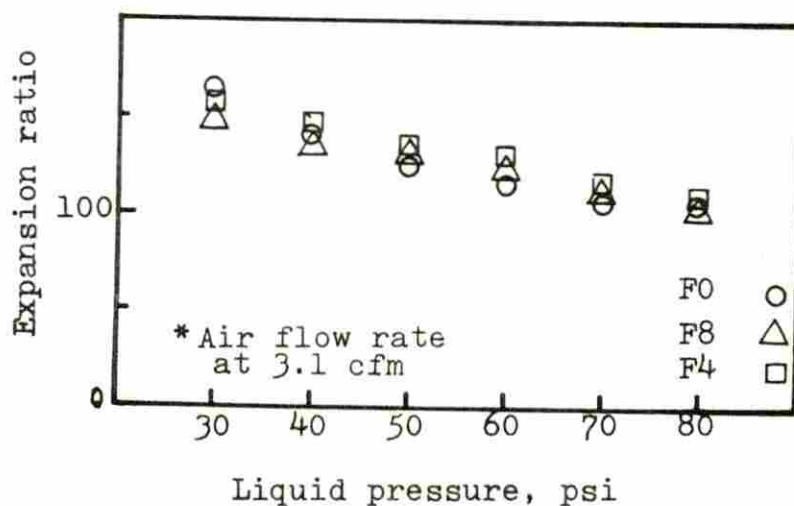


Figure 30. Effects of liquid pressure on expansion ratio with addition of Furadan insecticide

set constant at 3.1 cfm. The ANOVA tables are arranged in Appendix A. The difference between individual treatments--F0, F8, F4, was significant at the 0.5% level in the case of the constant air flow rate, but not significant under the condition of constant pressure. The principal reason is that the coefficient of variation for the latter was double that of the former condition. As a matter of fact, changes of liquid pressure will introduce more solution to join the response, which might magnify their differences.

It is interesting to note that, in Figure 29, the response of F4 was lower than the others but it was higher than the others in Figure 30. However, little is known about this situation this time.

Mathematical Expression To fit the expansion of foam with all possible variables and their combinations, a regression procedure was employed by using the SAS (Statistical Analysis System) computer language (3). The equation is listed as follows:

$$\begin{aligned}
 E = & 5.32 + 131.65 \alpha_F + 11.24 A_F - 0.36 P_\ell \\
 & - 2.92 A_F^2 - 136.97 (\alpha_F)^2 + 0.13 P_\ell \times A_F \\
 & + 39.64 \alpha_F \times A_F \\
 & (R^2 = 0.9369)
 \end{aligned}
 \tag{30}$$

The analysis shows a 67% chance that equation 30 passes through the origin, or approximately 1. The pressure does not show as significantly as the other factors, but is still

Table 4. Regression equations for expansion ratio of Fomex foaming agent

Percentage of foaming agent %	Equations	R <sup>2</sup>
0.20	$E = 1^a + 30.36 A_F - 3.6 A_F^2$	0.8581
0.25	$E = 1 + 30.2 A_F - 3.75 A_F^2 + 0.066 A_F \times P_\ell$	0.9155
0.50	$E = 1 + 30.6 A_F - 3.52 A_F^2 + 0.27 A_F \times P_\ell$	0.9594
1.00	$E = 1 + 41.41 A_F - 0.10 A_F \times P_\ell$	0.9777

<sup>a</sup> The coefficient B<sub>0</sub>'s are not significantly different from zero. Therefore, the value 1 is substituted here to meet the actual conditions.

significant at the 5% level.

However, it should be pointed out that overconfidence on the complicated equation may lead to erroneous conclusions, for some variations are still unpredictable. There are some other simpler expressions for different percentages of Fomex foaming agent as shown in Table 4.

#### Foam Drainage

The gravitation and capillary action were considered as two forces that affect the foam drainage. If the gravitation force predominates inside the foam body, the drainage rate will be greater; but if the capillary force becomes strong, it will take a long period of time to drain the liquid out.

Table 5 illustrates a variance analysis for the liquid



Table 5. Analysis of variance for the foam drainage of FM foams  
Mean: 77.367 C.V.: 12.02%

Source of Variation	Degree of Freedom	Mean Square	F-Test
Replicates	2	1,764.933	--
Foams-F0, F8, A0 (F)	2	49,542.525	572.51 ***
Air flow rate ( $A_f$ )	3	444,659.074	5,138.45 ***
F x $A_f$	6	927.888	734.16 ***
Time (T)	9	63,530.949	10.72 ***
$A_f$ x T	27	6,257.648	72.31 ***
F x T	18	727.898	8.41 ***
F x $A_f$ x T	54	232.101	2.68 ***
Error	238	86.536	
Corrected total	359	6,209.264	

\*\*\* Significant difference at the 0.05% level.

that was drained from the foam body as a function of time. All the main effects and their interactions are highly significant at the 0.05% confidence level. Among those factors, air flow rates are acting as a main source of variation throughout this experiment.

Besides the total drained liquid, another property of foam in drainage is its drainage rate. Mathematically the drainage rate is simply the first derivative of the drained liquid versus time. A general view of an overall effect of these two characteristics is shown in Figure 31. The drained liquid increased with time while the drainage rate reached a maximum value and then decreased.



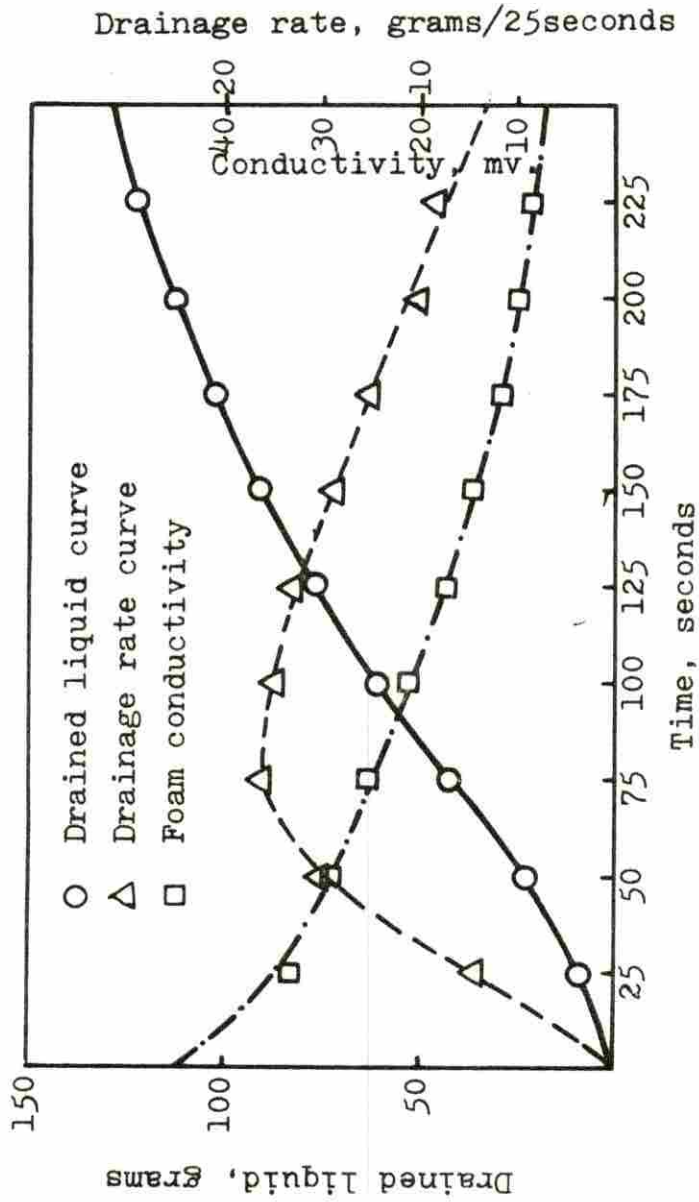


Figure 31. The overall effects of time on the foam drained liquid, drainage rate and conductivity

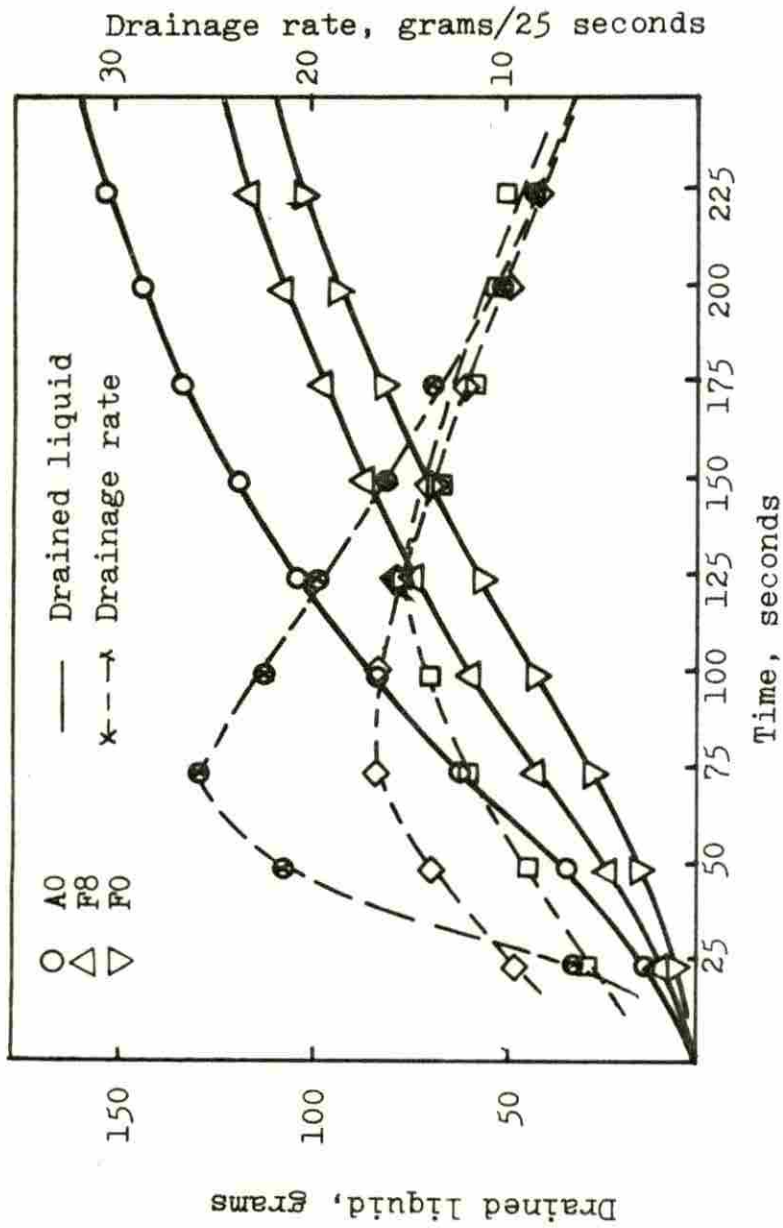


Figure 32. Effects of different types of foam on the drained liquid and drainage rate

Effects of Foaming Agents

Different types of foaming agents exhibited different results in drainage and drainage rate. Figure 32 illustrates these different situations of the following foam combinations: FO--FM without insecticide; F8--FM with 0.3% Furadan; AO--AG without insecticide. From the curve, it seems that the AO foam drains faster than the other two. From the point of view of foam stability or foam life, a foam with faster drainage may have less stability or shorter life. However, this is simply a statement without proof.

Another interesting fact is that foam with insecticide added will drain faster than that without insecticide. This is possibly due to the fact that the insecticide carrier tends to counter the effect of the foaming agent.

Effects of Air Flow Rates

Figure 33 shows the curves of foam drainage and drainage rate under different air flow rates by pooling the effects of other variables. It seems that foams generated at lower air flow rates drain faster than those generated at higher air flow rates. In Figure 21, we showed the capillary pores or the Plateau border which exerted a suction force on the draining liquid. As excess air was supplied, it took more liquid out of the capillary pores at the bubble walls. This increased the suction force and decreased the drainage rate. In fact, lower air flow rates generally generated foams with less expansion ratios (Figure 22). It took more solution to fill the same volume of the foam box. Consequently, more liquid drained out would be expected.

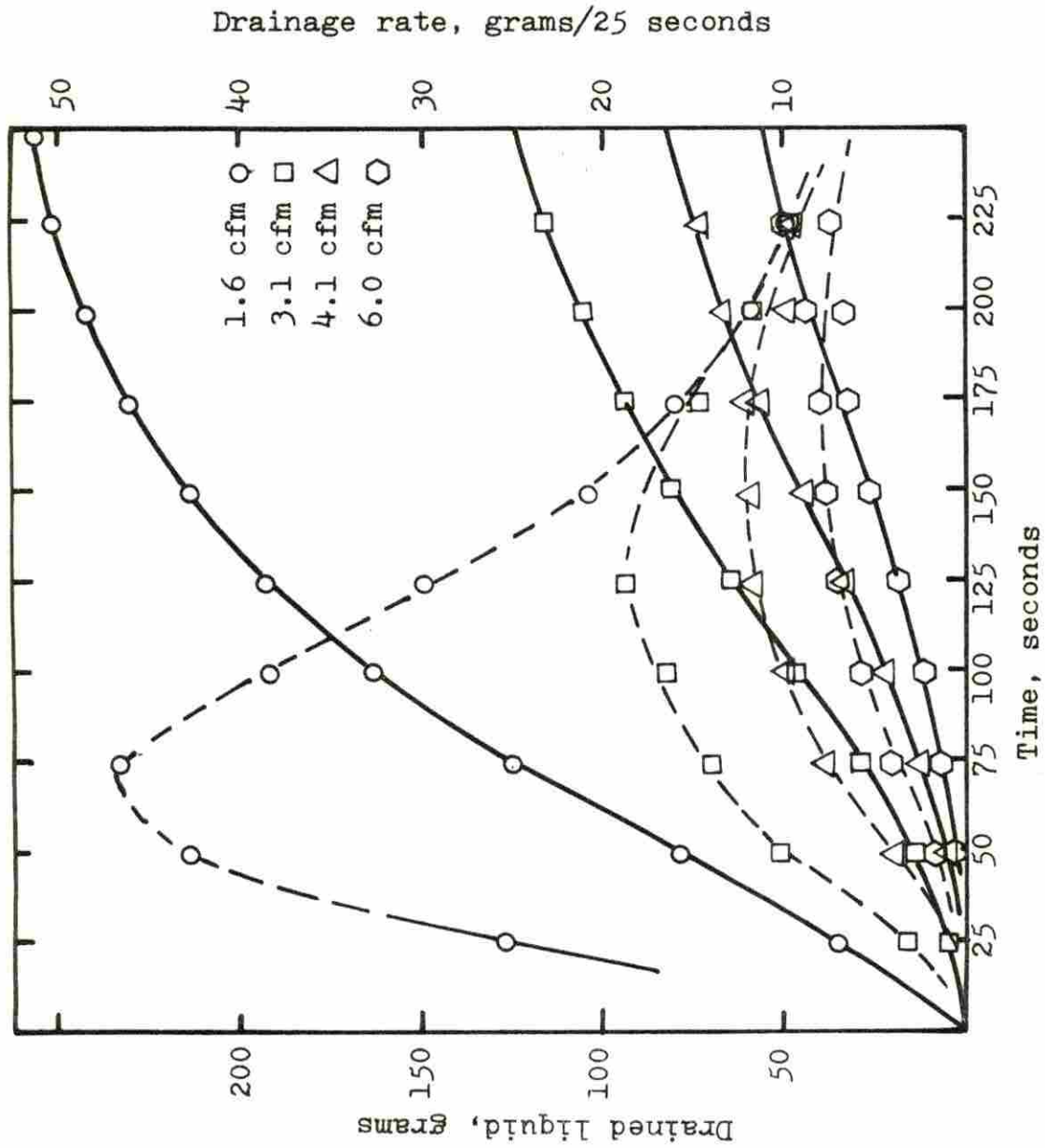


Figure 33. Effects of air flow rates on the foam drainage and drainage rate. (dash line represents drainage rate)

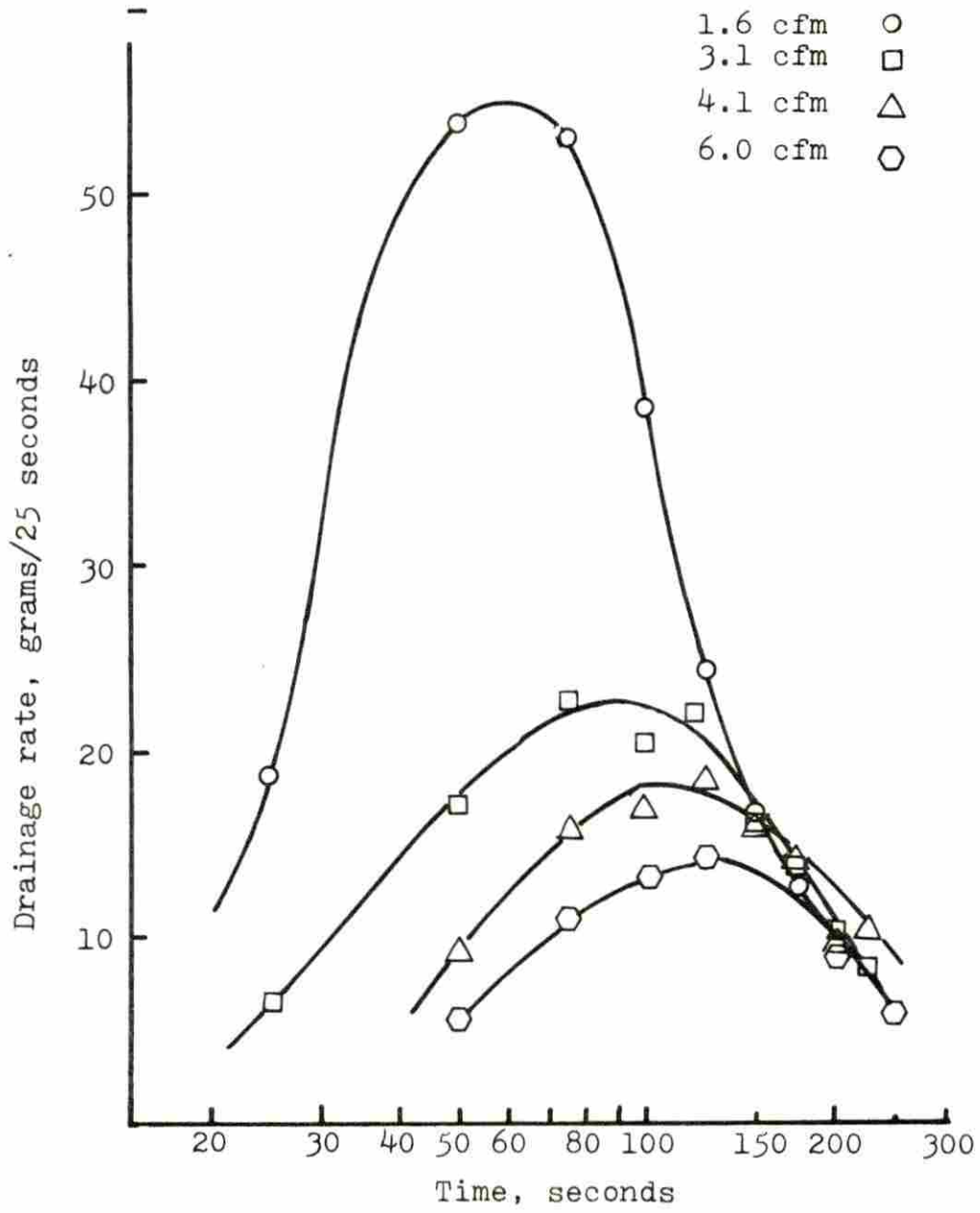


Figure 34. Drainage rate of AG-foam



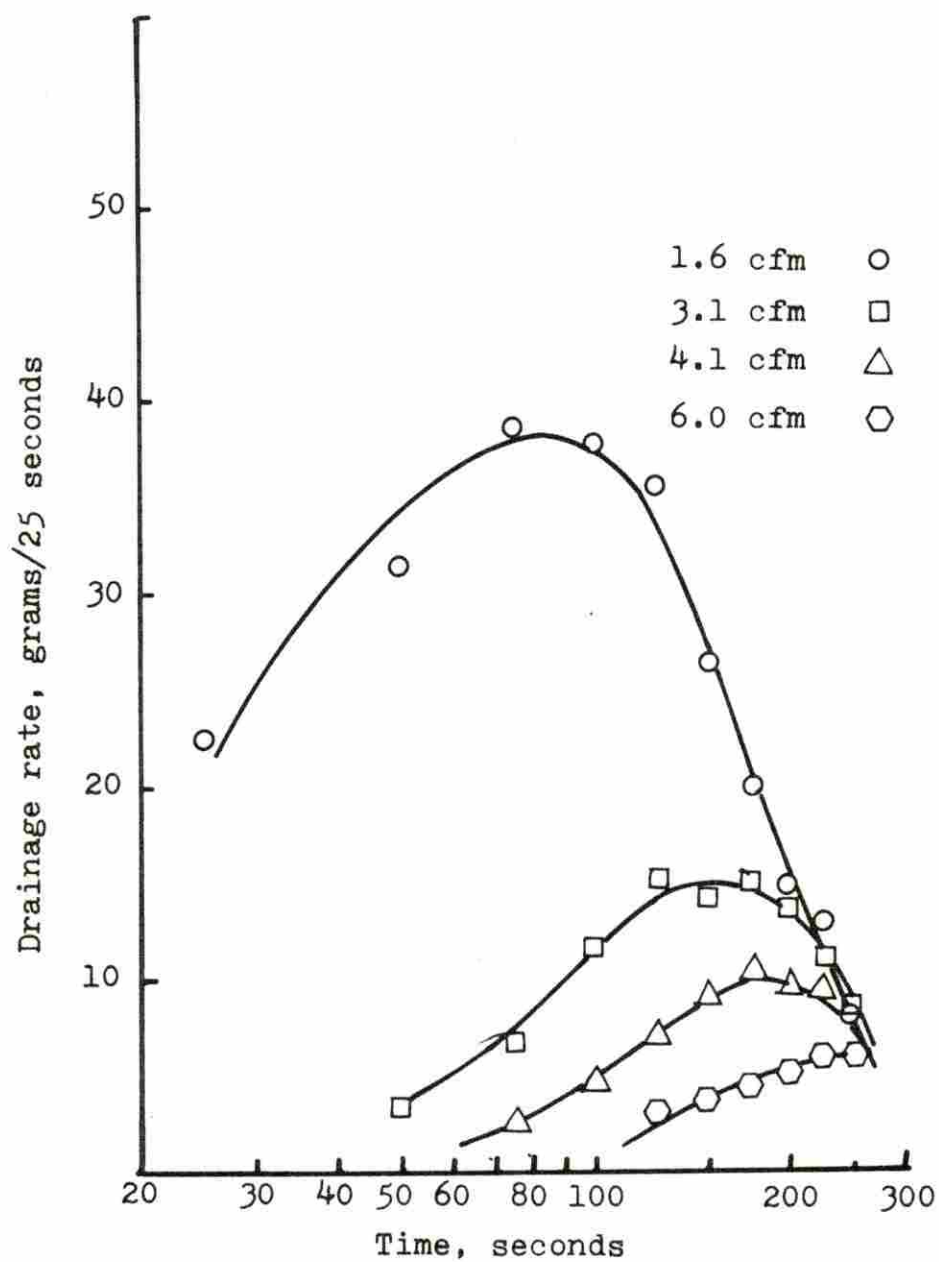


Figure 35. Drainage rate of Fomex foam without insecticide

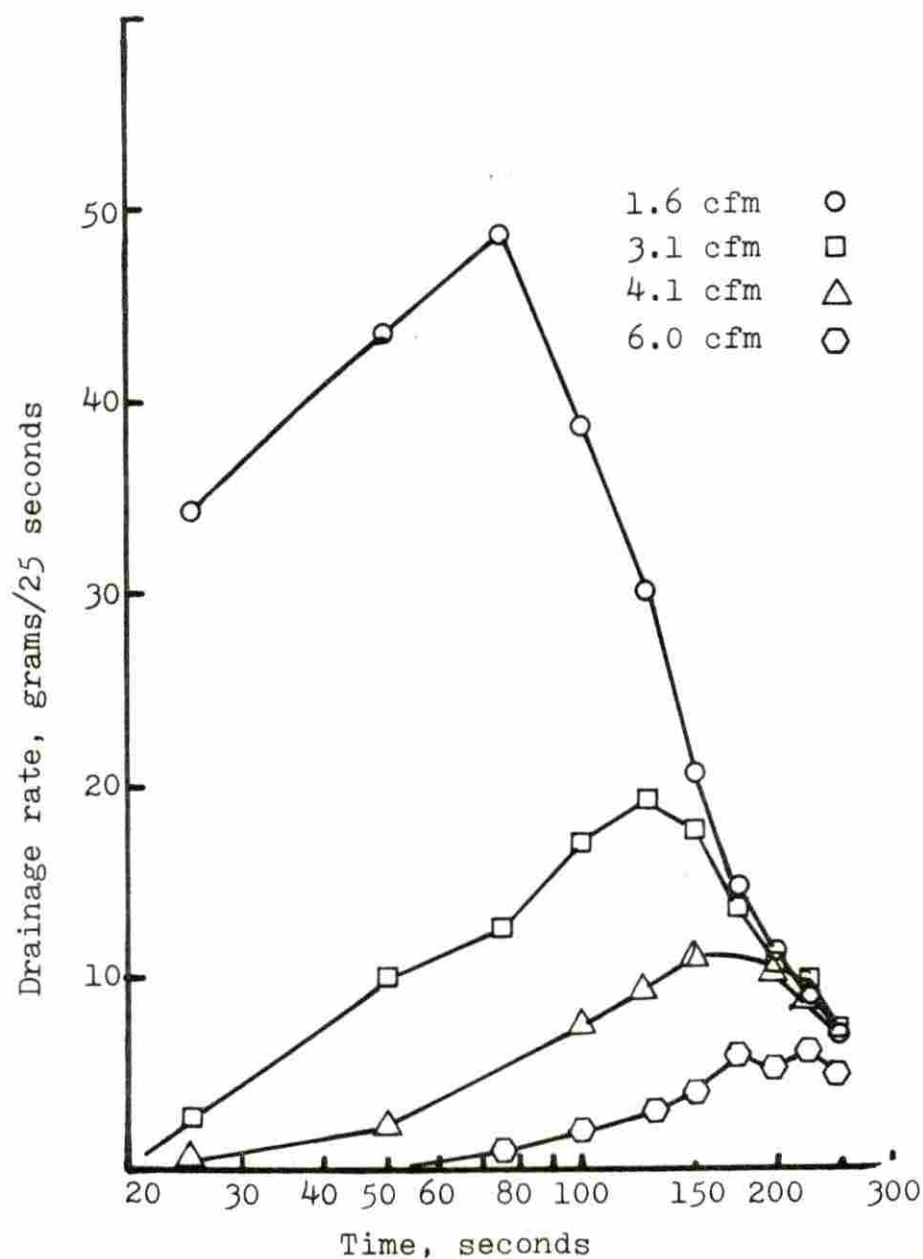


Figure 36. Drainage rate of Fomex foam with 0.3% of Furadan insecticide

To examine closer details in drainage rates, Figure 34, 35 and 36 are plotted to a semi-log scale. All curves are of the skewed bell-shaped type. The curves of AG foams appear closest to a normal distribution. For the other foams, the skewedness shifted from left to right gradually as the air flow rate increased. In other words, the time for the maximum drainage rate increased as air flow rates increased. Figure 37 shows this tendency, in which F0 has a constant increase while the others, F8 and A0 show a declining rate of increase.

Mathematical Expressions      Mathematical analysis of the drainage rate is quite complicated, and will then be suggested

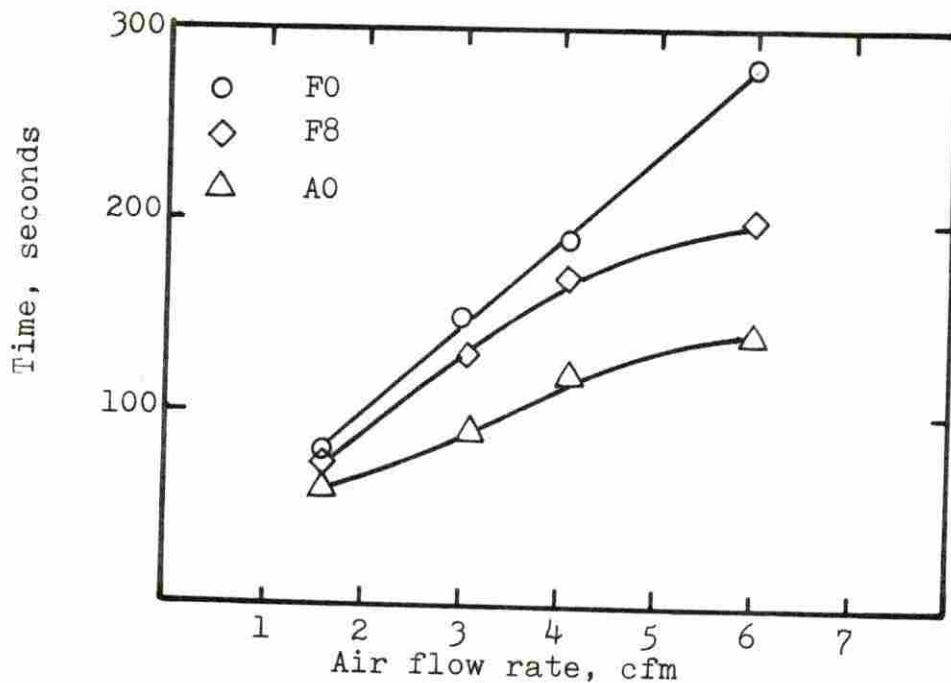


Figure 37. The time that maximum drainage rate occurs

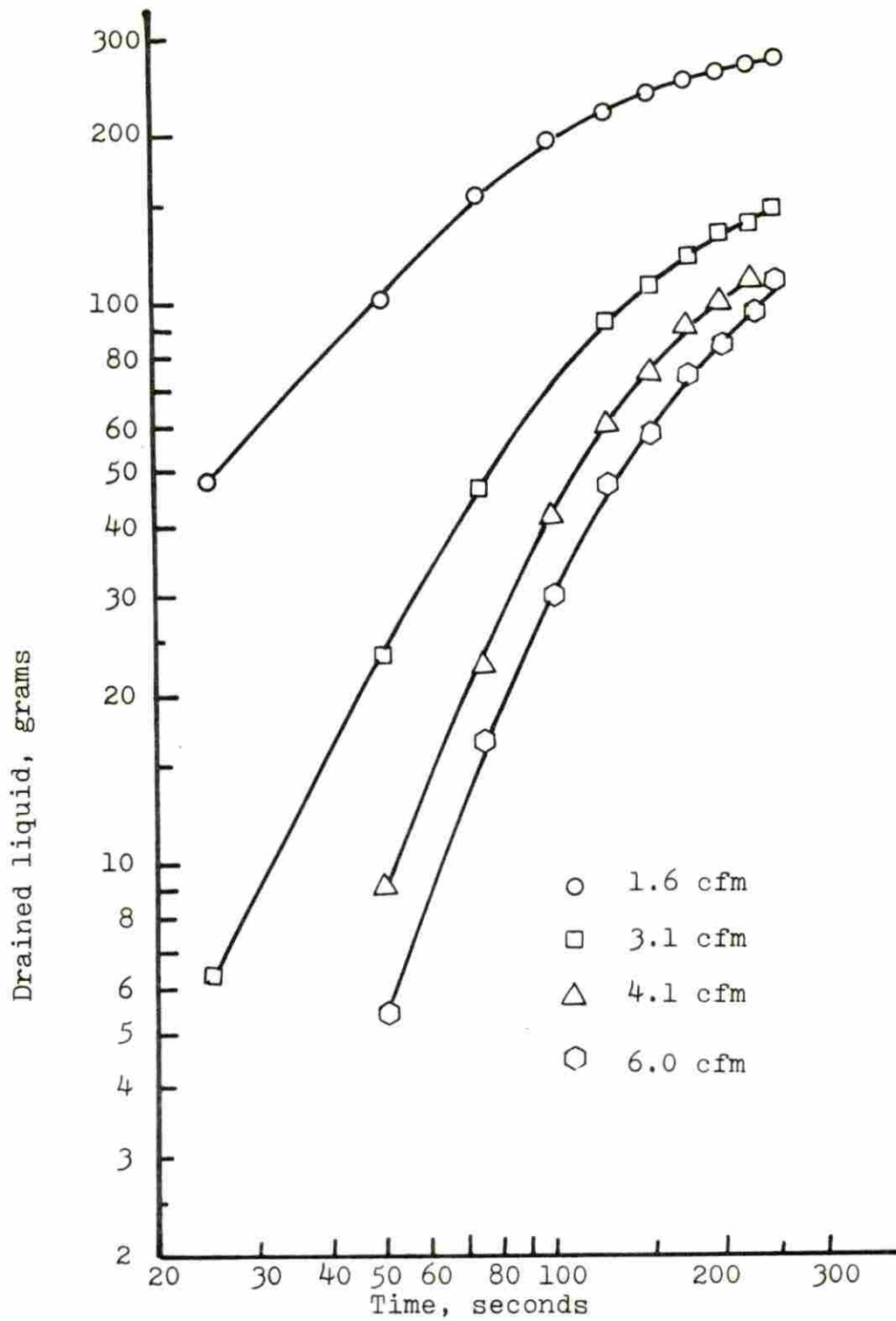


Figure 38. Drained liquid of AG foam on log-log scale

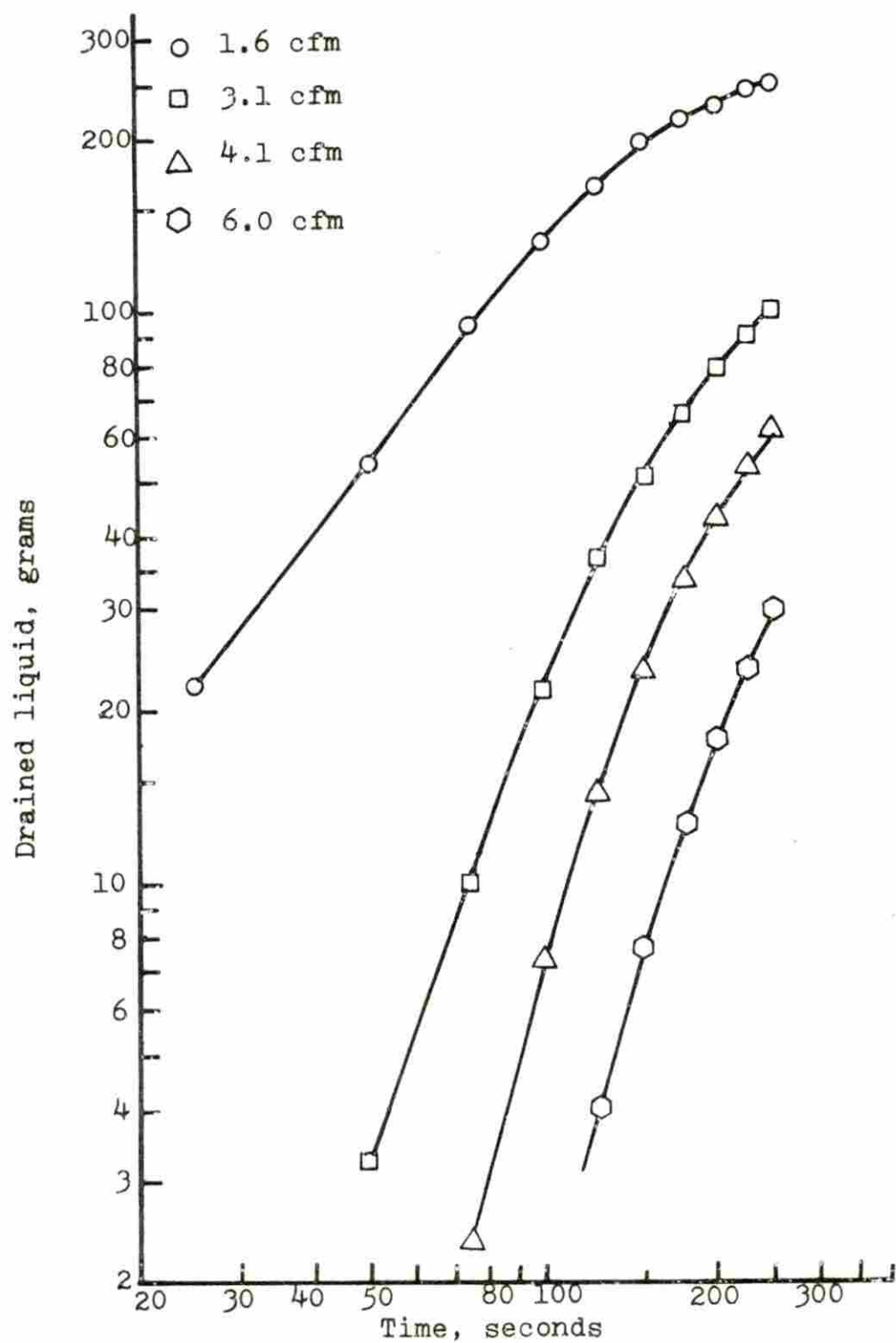


Figure 39. Drained liquid of Fomex foams on log-log scale



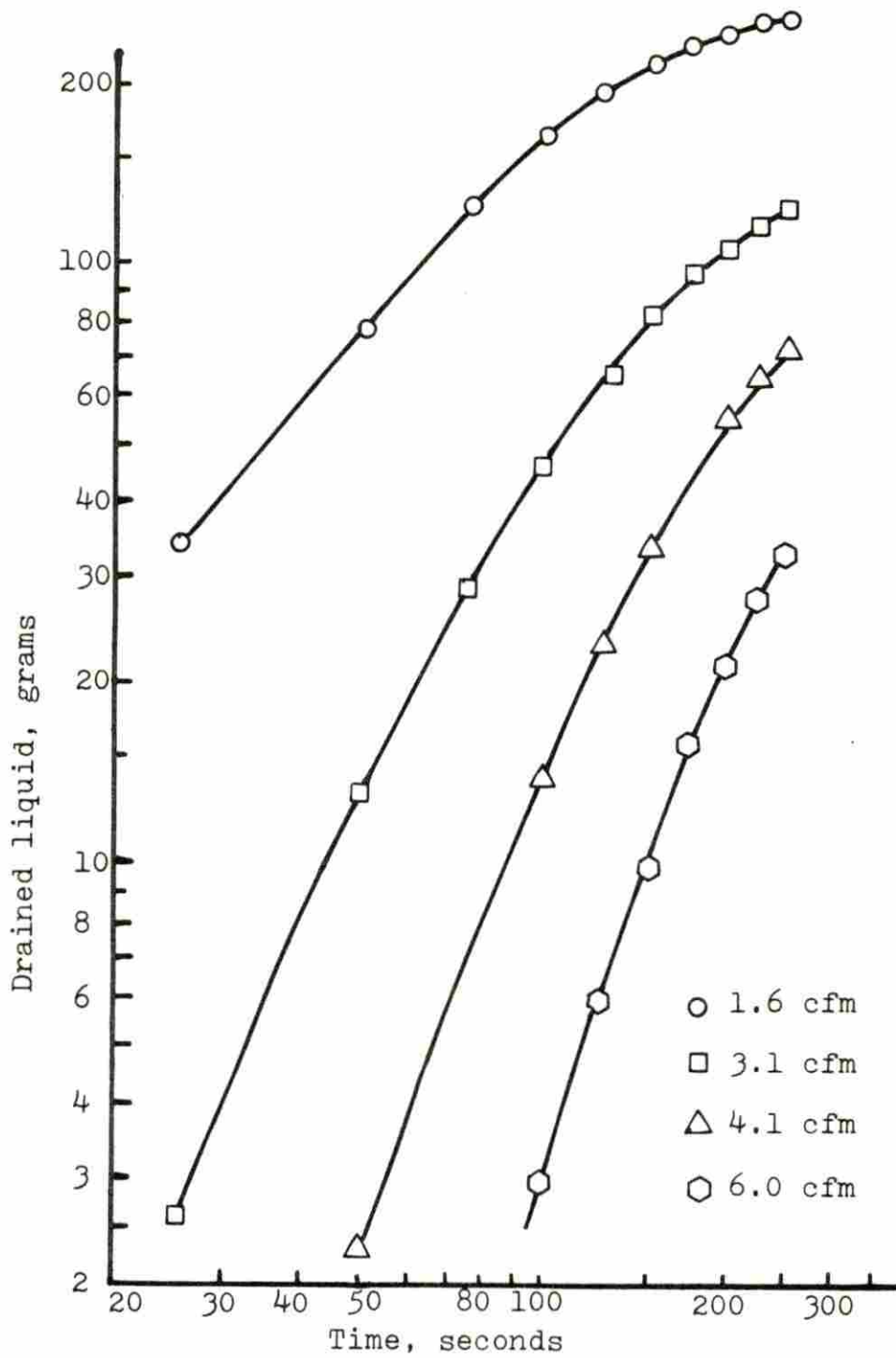


Figure 40. Drained liquid of Fomex foams with insecticide on a log-log scale

Table 6. Equations for foam drainage without considering the effects of foaming agents

Air flow rate (cfm)	Equations <sup>a</sup>	R <sup>2</sup>
---	$\ln Q = -20 - 0.67 A_f + 9.52 \ln T - 0.84 (\ln T)^2$	0.8572
1.6	$\ln Q = -3.72 + 3.05 \ln T - 0.25 (\ln T)^2$	0.9982
3.1	$\ln Q = -10.80 + 4.89 \ln T - 0.37 (\ln T)^2$	0.9995
4.1	$\ln Q = -30.31 + 12.26 \ln T - 1.09 (\ln T)^2$	0.9956
6.0	$\ln Q = -44.85 + 17.88 \ln T - 1.64 (\ln T)^2$	0.9876

<sup>a</sup> Units can be found in the notation section.

for further study. However, for the drained liquid, the curves can be improved by plotting them on a log-log scale as shown in Figure 38, 39 and 40, in which all curves possess a fair linearity. Therefore, by neglecting the difference in foaming agents, or by fitting equations for the curves in Figure 33, the results of regression analysis listed on Table 6 are obtained. Equations that fit the drained liquid curves of Figure 38, 39 and 40 are given in Appendix B.

#### Foam Conductivity

Electrical conductivity is another property that might

characterize foam bubbles. Use of this conductivity technique, however, may be quite controversial because too little was known so far as the principle is concerned. Also, because the resistance across the foam box was so high and the current passing through the circuit was so low, fears were that some other unknown factors might enter into the response without being noticed.

Presumably, the reason for the changes of conductivity may be principally due to the thinning of the bubble walls and the decrease of the size of the capillary pores, or, accordingly, the drainage rate. As a result, the conductivity will also be expected to change with the dynamic expansion ratio of foams under test.

Figure 41, 42, 43 and 44 show a series of changes of relative conductivity in millivolts versus time for different foams, as recorded by an X-Y plotter. The foams included four combinations of foaming agents and insecticide, F0, F4, F8 and A0 with four different air flow rates each. The analysis of variance is shown in Table 7, in which all main effects and their interactions were highly significant at the 0.05% confidence level. It is also worth noting that a great difference of conductivity between different foaming agents might hinder the use of a scale for the classification of foams.

Effects of Foaming Agents      Figure 45 shows the pooling effects of foaming agents, F0, F8 and A0. Apparently, AG foam possesses a lower conductivity than the others do. Addition

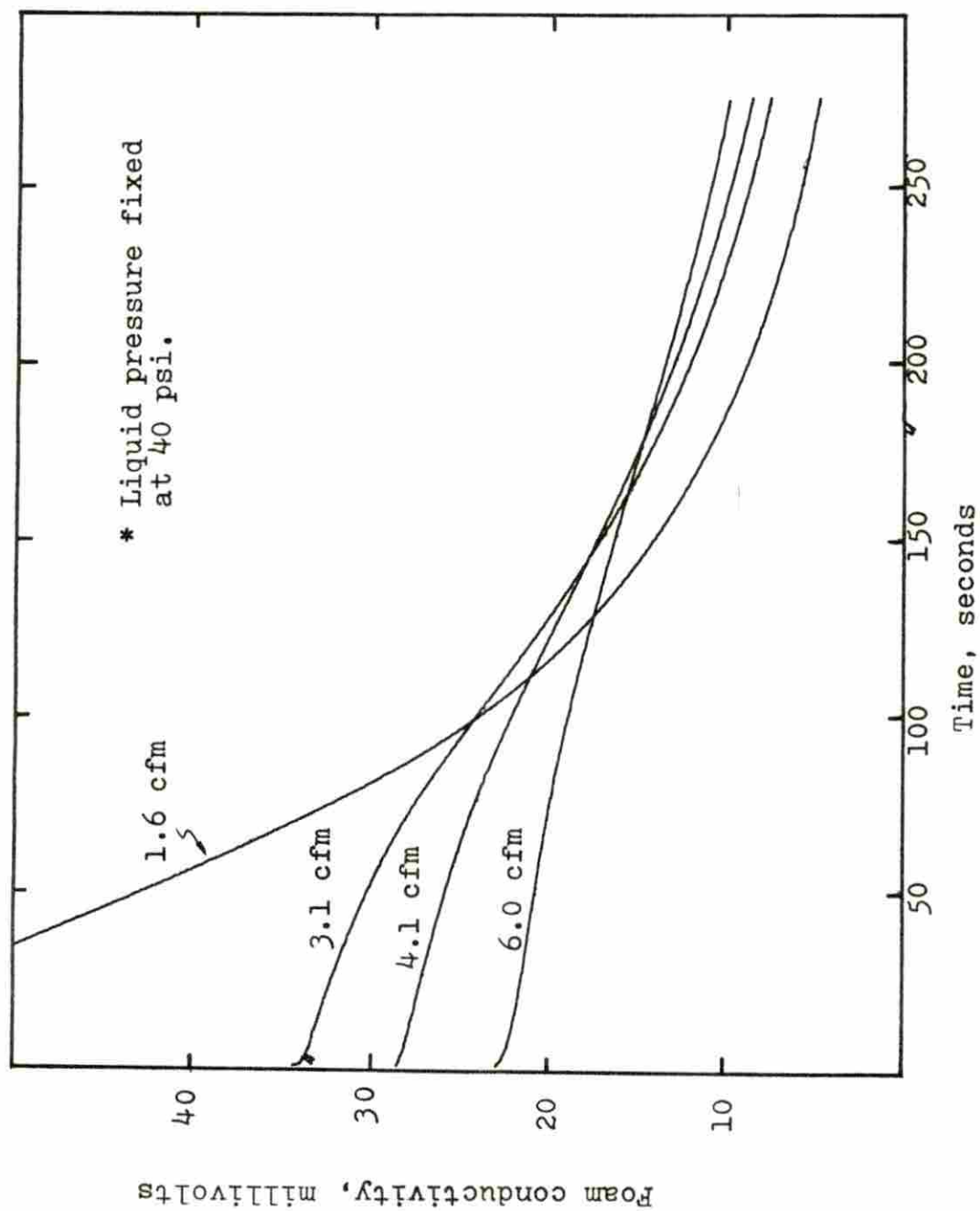


Figure 41. Electrical conductivity of F0 foams in different air flow rate

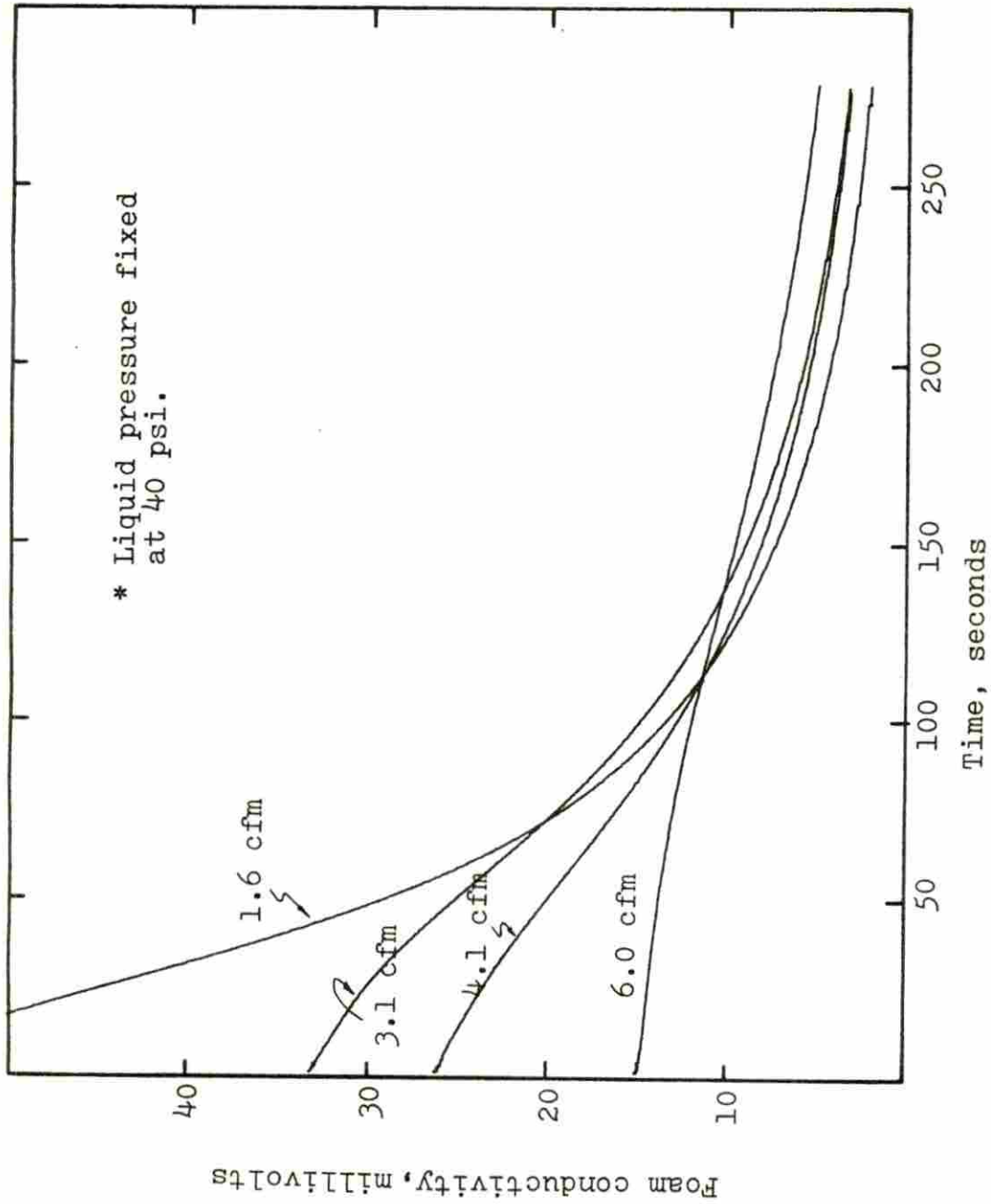


Figure 42. Electrical conductivity of F4 foams in different air flow rate



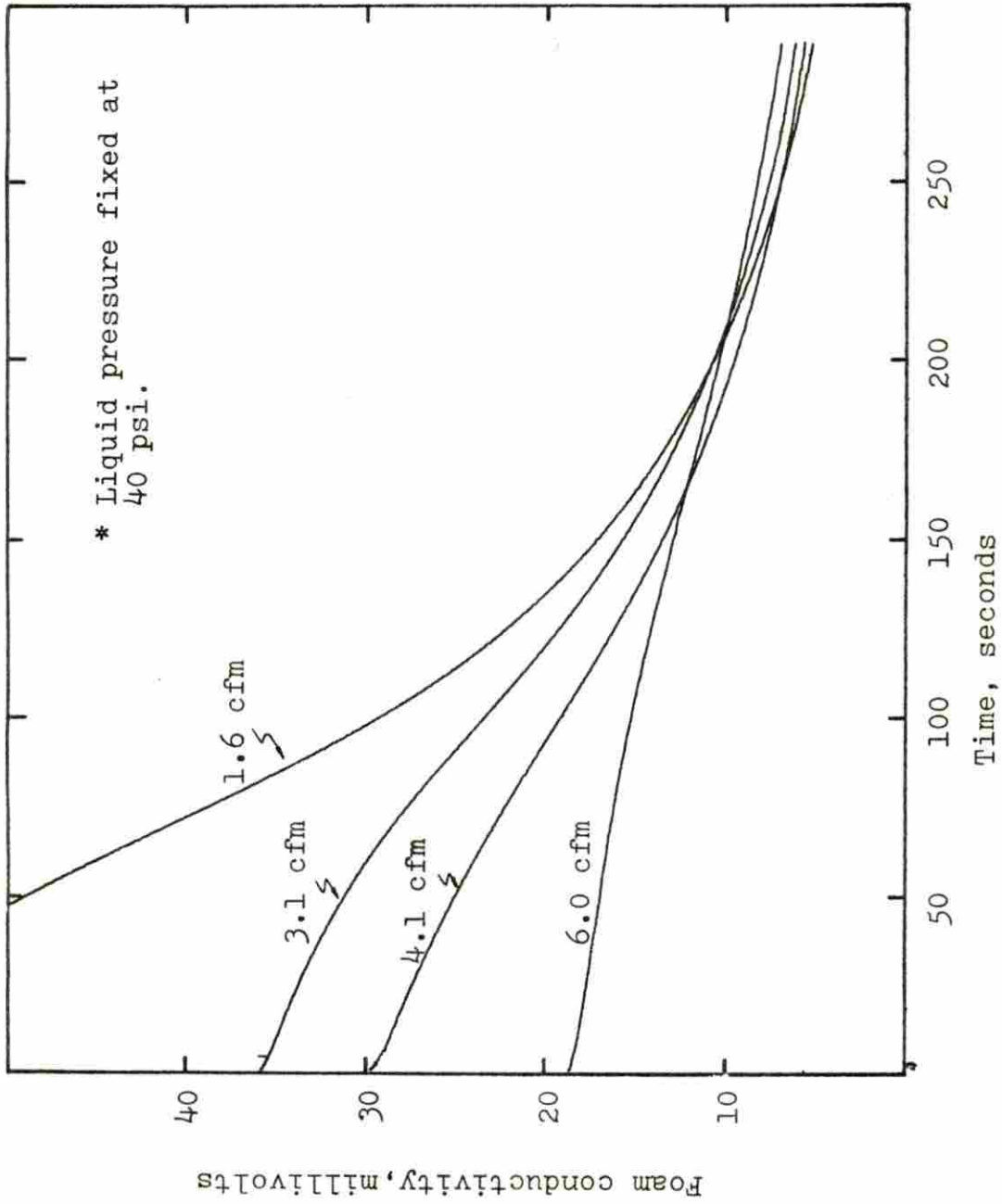


Figure 43. Electrical conductivity of F8 foams in different air flow rate

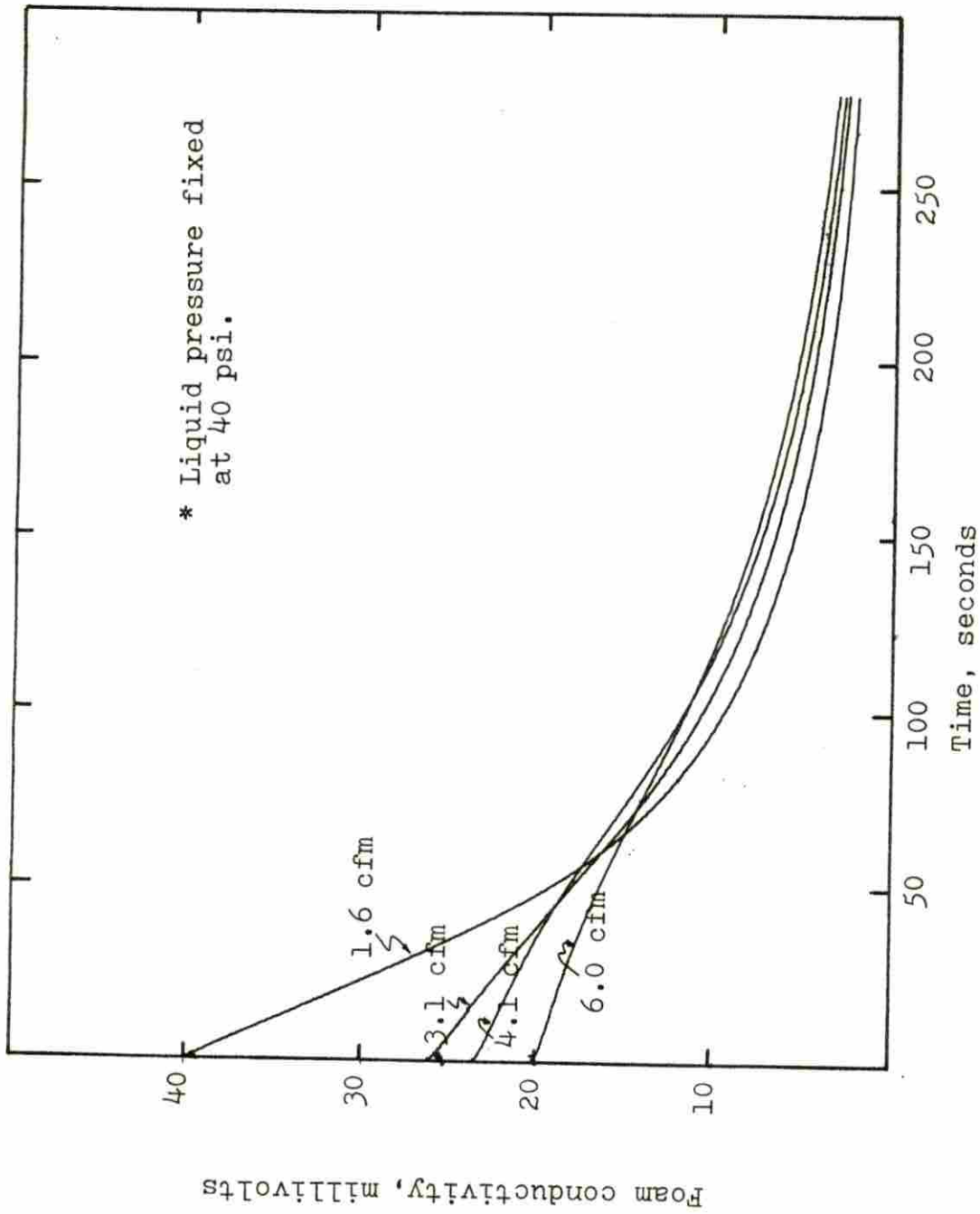


Figure 44. Electrical conductivity of A0 foams in different air flow rate

Table 7. Analysis of variance for the foam electrical conductivity

Mean: 17.942 C.V.: 15.81%

Source of Variation	Degree of Freedom	Mean Square	F-Test
Replicates	2	241.219	--
Foams--A0,F0,F8 (F)	2	2,539.378	315.627 ***
Air flow rate ( $A_f$ )	3	1,266.831	157.458 ***
F x $A_f$	6	187.990	23.366 ***
Time (T)	9	3,070.916	381.694 ***
F x T	18	16.715	2.077 **
$A_f$ x T	27	339.572	42.206 ***
F x $A_f$ x T	54	24.395	3.032 ***
Error	238	8.045	
Corrected total	359	141.586	

\*\*\* Significant difference at the 0.05% level.

\*\* Significant difference at the 0.1% level.

of insecticide Furadan to FM foam caused the conductivity readings to decrease.

#### Effects of Air Flow Rates

The air flow rate affected not only the foam drainage we discussed but the foam conductivity also. In Figure 46, foams generated at a lower air flow rate gave higher initial conductivity and higher decreasing rate. This may be because the foam bubbles contained more liquid and , consequently, provided a better passage for electrons. Besides, the low-air-flow foams drained at a considerably faster rate and thus reduced the effective area of the conducting path. An interesting fact is that all curves in

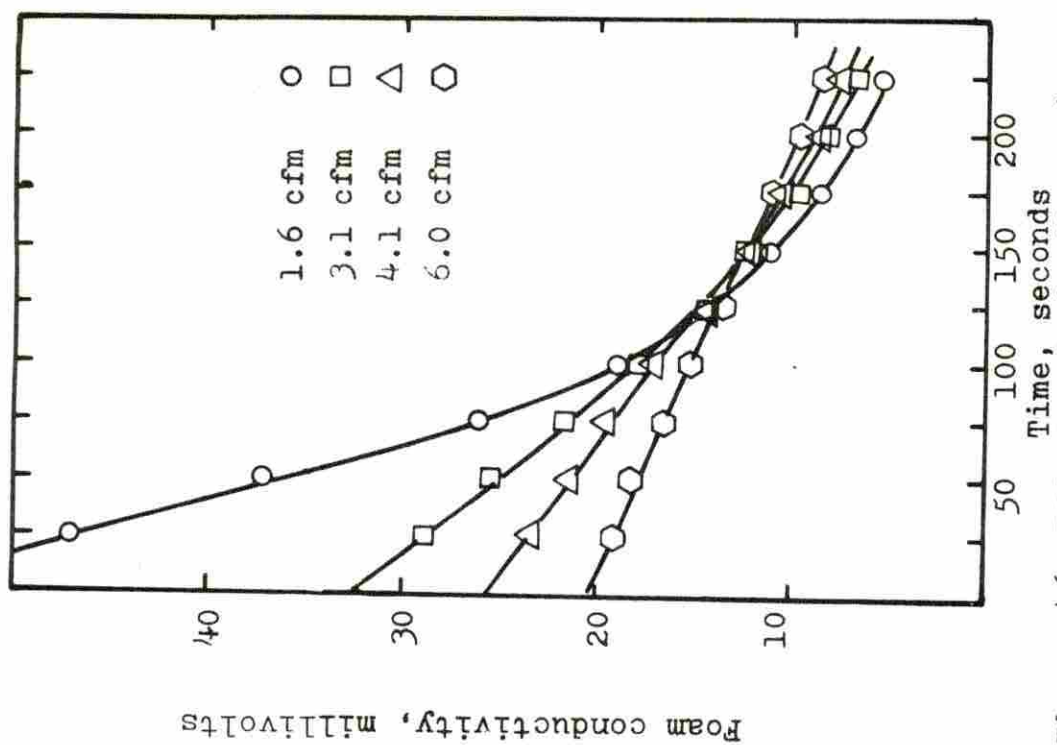


Figure 45. Effects of foaming agents on electrical conductivity.

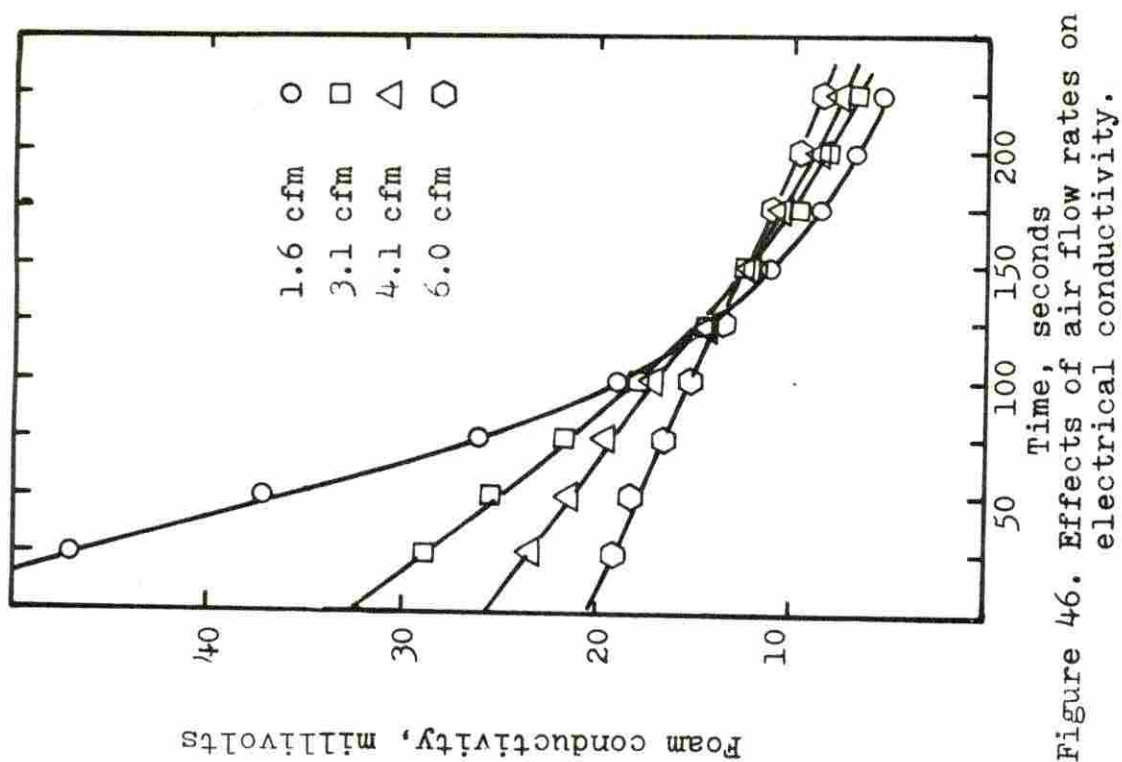


Figure 46. Effects of air flow rates on electrical conductivity.

in Figure 41-44 and 46 will eventually intersect and after that the status of conductivity compared to the first time period is completely reversed.

Conductivity and Drainage      A basic reason for using the foam conductivity to try to predict the other properties such as drainage rate, foam expansion ratio, etc., was that the conductivity can be measured easily and quickly. These attempts have the following basis:

a. Conductivity of foam possesses a decreasing function as the drainage rate does right after its maximum point is reached. This is specially true when watery foams are encountered.

b. In general, foam conductivity can usually be expressed as an exponential function,

$$\sigma = C e^{-k_0 t} \quad (31)$$

in which  $C$  and  $k_0$  are constant. Referring to equation 21 and letting  $\phi(t) = 1 - e^{-k_1 t}$  as used by most early researchers (5). Equation 21 then becomes:

$$E = E_0 e^{k_1 t} \quad (32)$$

Where  $E_0$  is the initial expansion ratio, and  $k_1$  is a constant. By comparing those two equations, it is suspected that expansion ratio implies a reciprocal relation with foam conductivity. To prove this relation may need further advanced studies.

Mathematical expression of drainage rate,  $v$ , in terms of



Table 8. Equations for foam conductivity by different air flow rates

Air Flow Rate (cfm)	Equations <sup>a</sup>	R <sup>2</sup>
1.6	$\ln \sigma = 4.34 - 0.01 T$	0.9960
3.1	$\ln \sigma = 124.53 - 36.88 T$	0.9942
4.1	$\ln \sigma = 95.37 - 23.4 T$	0.9856
6.0	$\ln \sigma = 110.25 - 21.47 T$	0.9829

<sup>a</sup> The unit of each term can be found in the notation section.

conductivity,  $\sigma$ , is derived by statistical methods and is given by:

$$v = 3.303 + 0.52 \sigma \quad (R^2 = 0.2751) \quad (33)$$

Unfortunately, the value of R-square is pretty small. The problem is that the time the X-Y plotter measured was not identical to the time the liquid drained out. Actually the draining liquid took a period of time to travel from the vicinity of the copper plates to the drain hole.

Table 8 shows other regression equations for each air flow rate (as in Figure 46). For more details about equations for each type of foaming agents, see Appendix C.

$\Delta$ -Conductivity Another experiment for foam conductivity was measured from the discharge V-shaped box attached to the foam generator. For convenience, it will be called " $\Delta$ -conductivity" throughout the discussion. This measurement

provides a quick reading from the freshly generated foams without introducing any collapse effect. Two separate sets of measurements were conducted: one kept pressure constant at 40 psi and varied the air flow rate; the other kept the air flow rate constant at 3.1 cfm and varied the liquid pressure. The ANOVA tables of both conditions are arranged in Appendix D. Tables show both air flow rate and liquid pressure are main sources of variation. Again, the effects of foaming agents still appear quite significant in the conductivity response. In Figure 47 and 48, it seems that conductivity of F4 was higher than that of F0 but F8, on the contrary, had a lower value than F0 did. Little is known about this phenomenon whatsoever, but this phenomenon also occurred on expansion ratio in Figure 29 and 30 as we discussed before.

To express expansion ratio in terms of  $\Delta$ -conductivity, the equations were derived:

a. For constant air flow rate at 3.1 cfm:

$$E = 186.5 - 2.40 \sigma_{\Delta} \quad (R^2 = 0.8431) \quad (34a)$$

b. For constant liquid pressure at 40 psi:

$$E = 233.2 - 5 \sigma_{\Delta} \quad (R^2 = 0.8289) \quad (34b)$$

Unfortunately, these two equations are not quite identical. It is doubtful that foams with the similar expansion ratio would exhibit the same other characteristics at the same conditions. Sometimes this discrepancy is obvious if both fresh

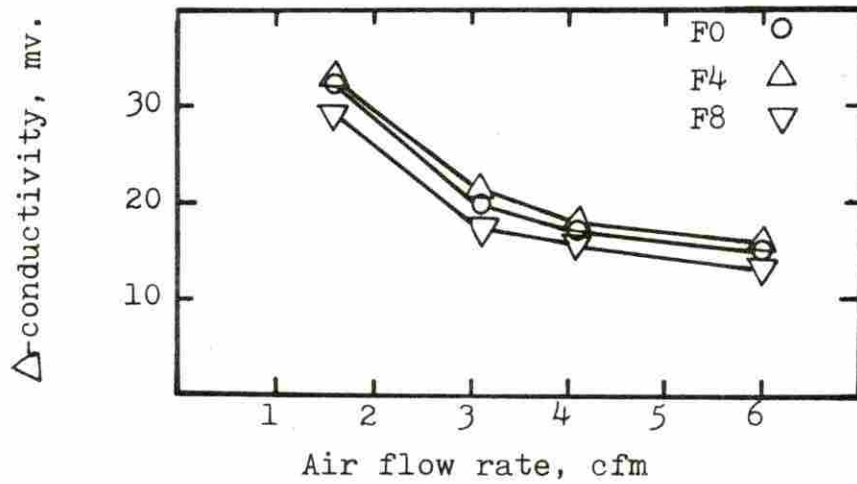


Figure 47.  $\Delta$ -conductivity of 1% Fomex foams by varying air flow rate. The liquid pressure was fixed at 40 psi.

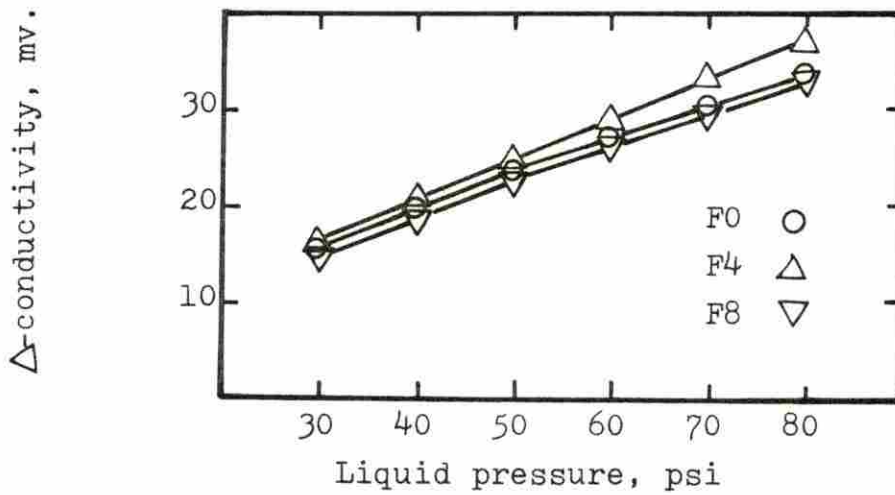


Figure 48.  $\Delta$ -conductivity of 1% Fomex foams by varying liquid pressure. The air flow was fixed at 3.1 cfm.

and aged foams are under consideration. They may have the same expansion ratio at some certain time but their drainage characteristics and quality are completely different.

To make these equations available, a line that passes through the intersection of equation 34a and 34b with a slope average was then chosen as in Figure 49. The new equation is

$$E = 210 - 3.7 \sigma_{\Delta} \quad (35)$$

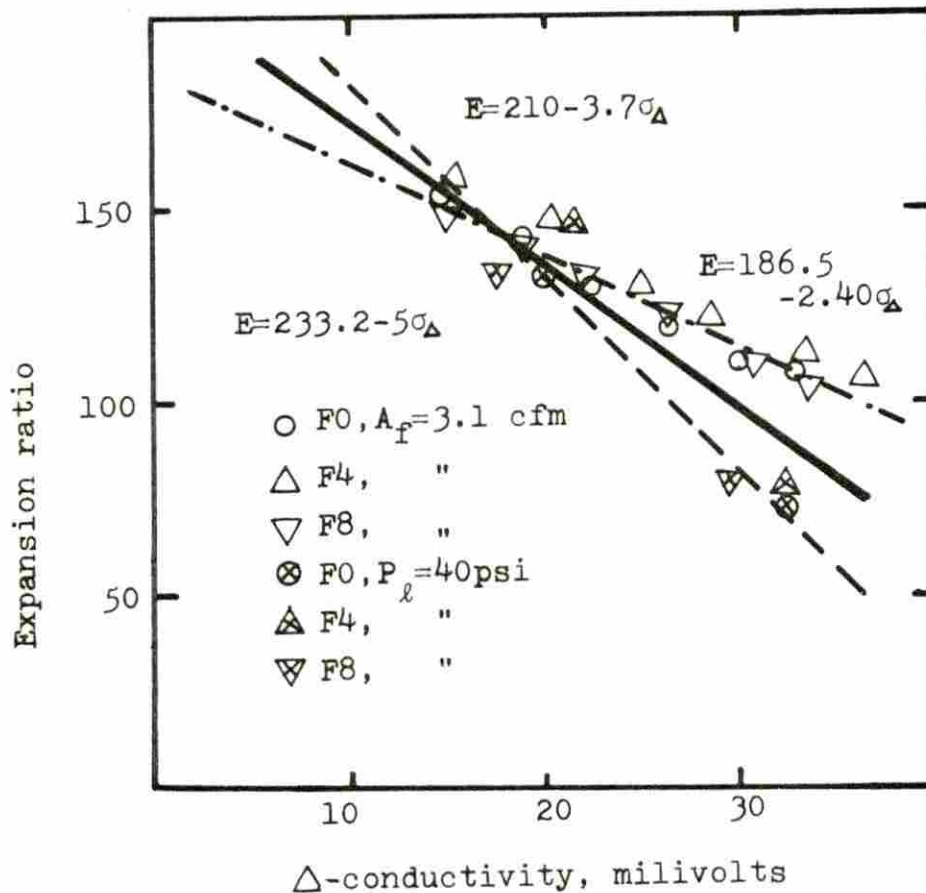


Figure 49. Relation between expansion ratio and Δ-conductivity

## Foam Classification

Foam index is another method for the foam classification purpose. However, this index method only works within a restrictive range. Both too high air flow rate and too low percentage of foaming agent will ruin this index system. Fortunately, this working range fell within the range needed for the insecticide study. Therefore, some successful results will be expected. Appendix E contains the ANOVA tables for the variables, air flow rate, back pressure ratio, and expansion ratio, which were supposed to be related to the foam index. The experiment was conducted by fixing the liquid pressure at 40 psi.

Response of Air Flow Rates From Figure 50, it is obvious that air flow rate steadily increased with the index number. The percentage of foaming agent did affect the behavior of air flow rates some certain amount.

The effects on air flow rates when insecticide Furadan was added are shown on Figure 51. It seems that the insecticide did not change much of the air flow response, but this conclusion could be wrong because the experiments with addition of insecticide were performed once only.

The equation for the curves in Figure 50 can be expressed as:

$$A_w = 0.89 - 0.669 \alpha_f - 0.35 N + 0.116 N^2 \quad R^2=0.8702 \quad (36)$$



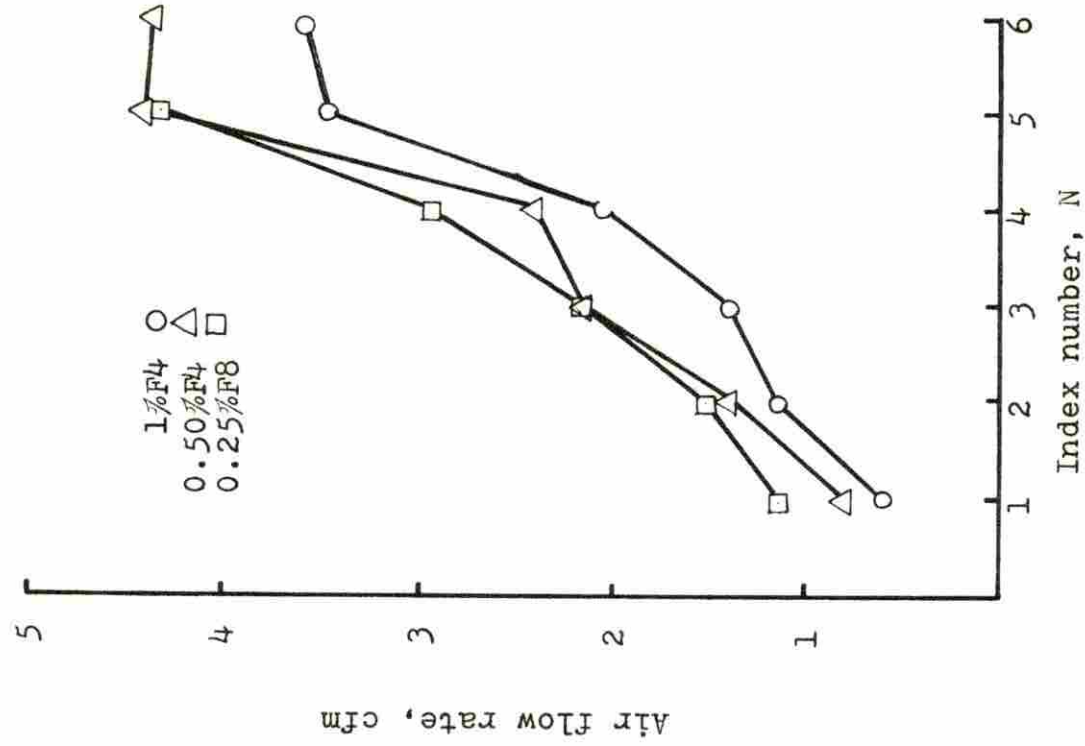


Figure 51. Relations of air flow and N with addition of Furadan

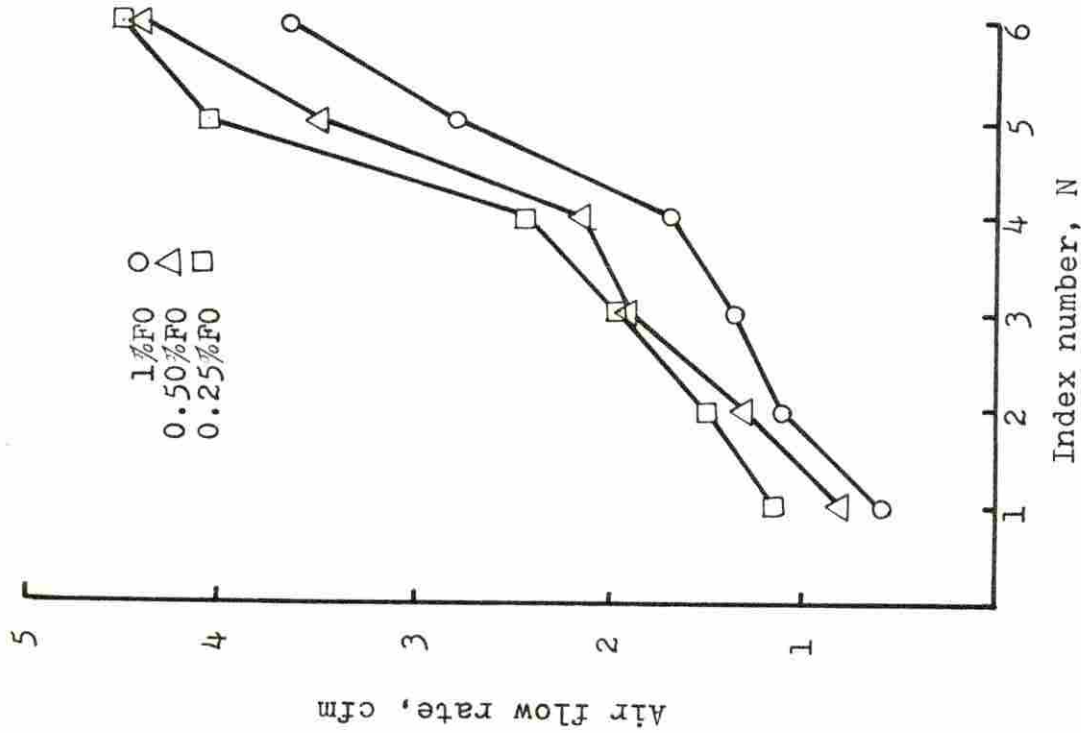


Figure 50. Relations of air flow rate and the index number, N, varying the % of foaming agent (FW)

Here,  $A_w$  is expressed in inches of water level in the manometer. Equation 12 may be applied if air flow rates are needed.

Response of Back Pressure Ratio      Back pressure ratio is a ratio of water level pressure at the chamber of the foam generator to that of the air flow rate. Figure 52 and 53 show conditions with and without insecticide added.

The equation for the back pressure ratio in terms of index number is:

$$\gamma_b = 6.63 - 1.041 N \quad (R^2 = 0.7061) \quad (37)$$

Response of Expansion Ratio      The relationship between the index number and the foam expansion ratio is of greatest interest to us. From the ANOVA table, the index number acts as an important source of variation for the expansion ratio. In Figure 54, it is interesting to note that when the index number was less than 4, the expansion ratio appeared a linear function with index number and then became irregular when the index was over 4. The foams with addition of the insecticide Furadan did not have this characteristics but still followed Figure 54 without any serious deviation.

An equation for the expansion ratio is expressed as follows:

$$E = 22.65 + 1.798 N^2 \quad (R^2 = 0.8612) \quad (38)$$

### Field Applications

In the field experiment, the killing effect of insecticide with foam carrier was expressed in terms of the number of

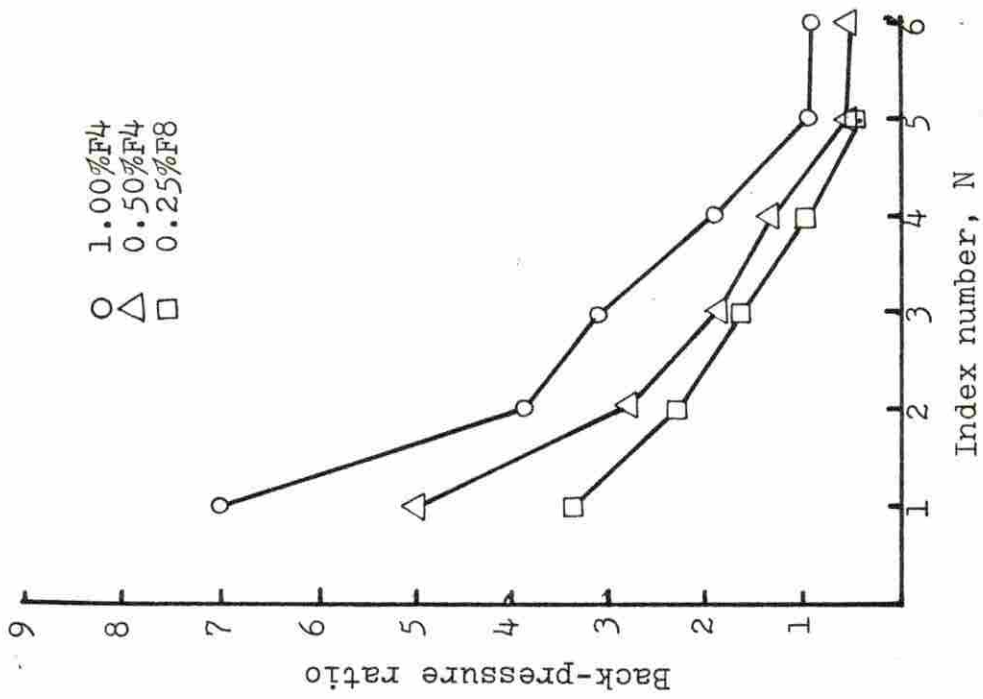


Figure 52. Relation of back-pressure ratio and index number

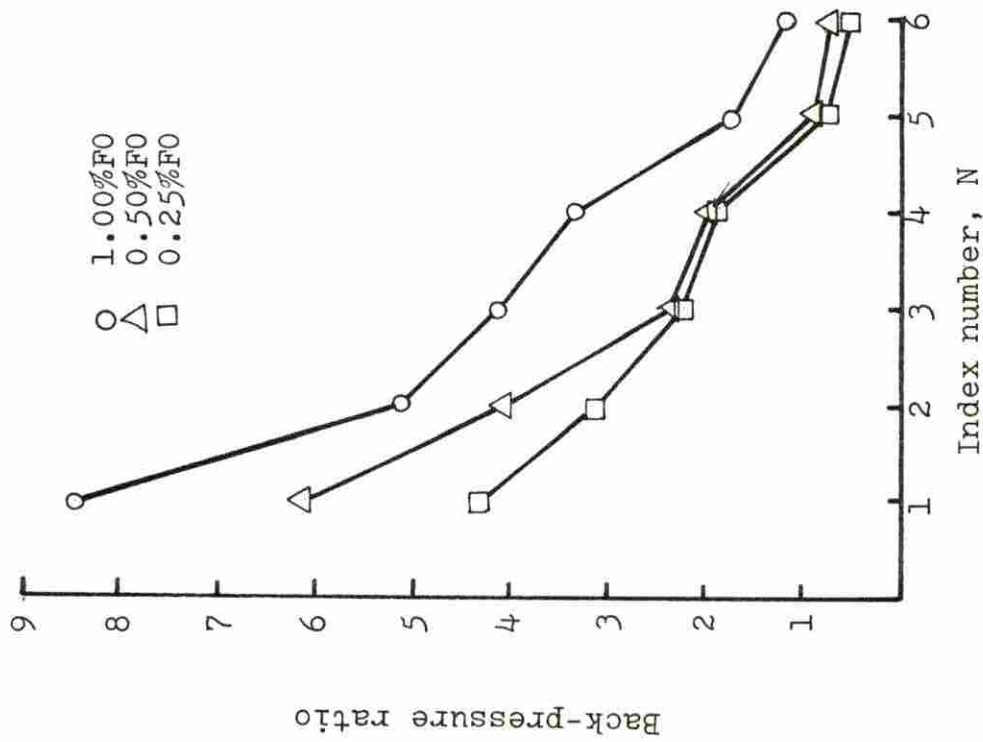


Figure 53. Relation of back-pressure ratio and index number with addition of Furadan

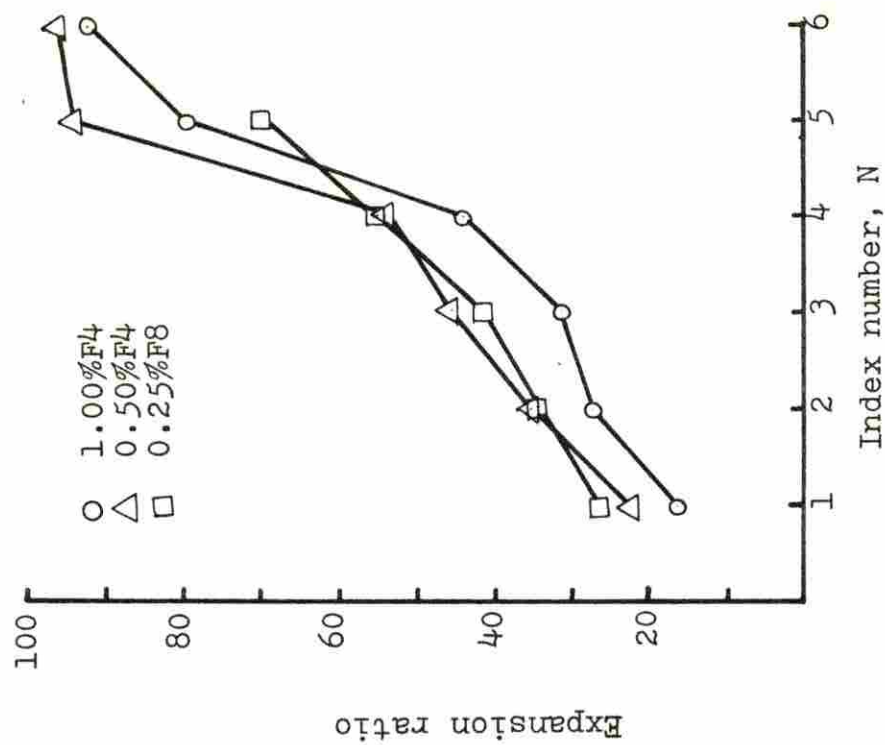


Figure 54. Relation of expansion ratio and index number

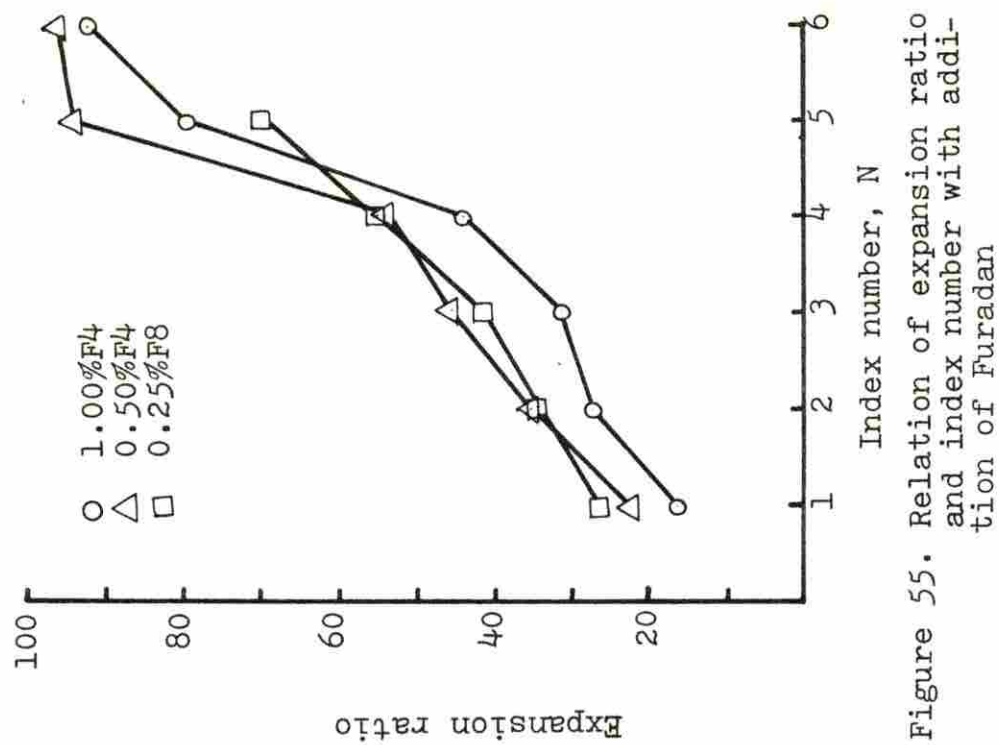


Figure 55. Relation of expansion ratio and index number with addition of Furadan

cavities per twenty plants in which the corn stalks were damaged by corn borers. The primary data are listed on Appendix F and a statistical analysis is shown in Table 9. Generally speaking, the foam carrier method had fair success in controlling the corn borer in comparison with the check plots if the 1% confidence level is chosen. But it will be a disap-

Table 9. Analysis of variance for corn borer control with foam carrier method

Mean: 30.25 C.V.: 29.71%

Source of Variation	Degree of Freedom	Sum of Square	Mean Square	F-Test
Blocks	3	1,303.934	434.65	---
Treatments	18	7,562.000	420.11	
Check vs. Others	1	5,054.400	5,054.40	62.57 **
Foams vs. Sprayer	1	1,150.52	1,150.52	14.24 **
Foam A vs. $\frac{\text{Foam(B+C)}}{2}$	1	311.76	311.76	3.86 *
Nozzle/Foams	1	192.00	192.00	2.37 ns <sup>a</sup>
$\alpha_f(\%)$ /Foams	1	65.19	65.19	0.81 ns
Nozzle x $\alpha_f$ /Foams	1	126.75	126.75	1.57 ns
Foams vs. Check <sup>b</sup>	1	728.02	728.03	10.25 **
Error	54	4,362.316	80.78	
Corrected total	75	13,228.250	176.38	

<sup>a</sup> Non-significant.

<sup>b</sup> The pair foams vs. check is not orthogonal to the others.

\*\* Significant difference at the 1% level.

\* Significant difference at the 5% level.



pointment if the spraying method is compared. However, the problem is that the machine application efficiency might also join in this response. The effect of the foam carrier method will thus be masked by its lower machine operating efficiency.

Among three types of foams, A, B, and C, type A foam exhibited better results than the others (5% level of significance). So far as we know, type A foam possessed a good drainage property and fair fluidity, allowing the foam bubbles to flow on the corn leaves and draining into the leaf sheath, killing the larvae of borers. Type B foam ( $E > 100$ ) had a great volume but had poor fluidity characteristics which would prevent from moving freely. Therefore, this type of foam would simply stay on top of leaves until it was dried out by evaporation and fail to reach the locations of the borer larvae.

However, type C foam ( $E < 20$ ) was a good one according to the above consideration. It had highest fluidity and would drain very well, too. But the difficulty of this type foam was that its stringy shape of foam column could not be directed by the machine to hit the right target on the corn plants.

As to the nozzle sizes and percentages of foaming agent in this experiment, the effects of both factors were not significant at all. The effect of nozzle within foams might be significant at a low confidence level, but this experiemnt failed to detect it.

## SUMMARY

The objectives of this study were to discover the characteristics of foams for use as an insecticide carrier as well as to formulate foam properties and to find a method of classification of foams. An attempt was also made to understand the applicability of foams as an insecticide carrier on corn borer control. To attain these objectives, a series of experiments were performed both in the laboratory and in the field.

Experiments were conducted at combinations of several levels of air flow rate, liquid pressure, and percentage of foaming agents. There were three types of foaming agents, Fomex, AG-foam and Fomark, in use. But actual study was focused on the Fomex foaming agent most of time. The insecticide Furadan was sometimes added to detect its effect on the foam characteristics.

Expansion ratio was the first property studied in the foam laboratory. Actually it has been an important property used to characterize foams throughout the foam history. However, a statistical analysis was employed to examine how the air flow rate, liquid pressure and percentage of foaming agents affect the foam expansion ratio. A regression equation was derived to serve this purpose.

Investigations on the foam drainage and foam electrical conductivity were conducted at the same time. It was found that fair correlation between the foam electrical conductivity

and the foam drainage rate existed and the expansion ratio of foam would affect the behavior of foam conductivity somehow.

Some efforts were made to derive a mathematical expression of foam characteristics, such as expansion ratio, foam drainage, etc., in terms of foam conductivity, which was measured in the discharge box of the foam generator, and the picture index system. The picture index was designed according to the shape of a falling foam column directly under the foam generator. Both designs worked with a fair success.

An experiment on use of foam as an insecticide carrier for corn borer control was conducted in the field. The results showed a failure to detect some of effects expected. However, the spray method was a better method for corn borer control as shown by the statistical analysis. There were no significant differences in borer control due to the nozzle sizes and percentages of foaming agent used. Foams with medium expansion ratio gave better control than the other types of foam.

## CONCLUSIONS

The following conclusions drawn from this study should be considered valid only for the foam generator, foaming agents, and range of variables that were used during these experiments.

1. Expansion Ratio

Air flow rate and percentage of foaming agent were the dominant factors affecting the expansion ratio of foams. The liquid pressure had less effect on expansion ratio than air flow rate and percent foaming agent, but it was still significant at the 5% confidence level.

There existed a minimum expansion ratio which is equal to 1 and a group of maximum values which formed a "ridge" when expansion ratio was plotted against the other variables. As the air flow rate increased, expansion ratio increased to a maximum on the A-side of the ridge, but decreased on the B-side (or passing the ridge).

Addition of foaming agent moved the maximum expansion ratio to some higher value.

No effects on the expansion ratio were detected with addition of insecticide--Furadan.

2. Foam Drainage

Among the foaming agents used, AG-foam exhibited a faster drainage rate. The quantity of the drained liquid and the maximum value of drainage rate increased with an increase of air flow rate, or with addition of insecticide.



The maximum drainage rate occurred at a later time when air flow rate was higher when generating foam. In general, the drainage rate had a skewed bell-shaped type of curve with respect to time when plotted on a semi-log scale. A general form of the drainage rate curve is:

$$Q = C_0 t^{(k_2 + k_3 \ln t)}$$

### 3. Foam Conductivity

Foams generated at a lower air flow rate gave a higher initial conductivity and higher decreasing rate. A general expression for conductivity is

$$\sigma = C_1 e^{-k_4 t}$$

The foam expansion ratio can be expressed in terms of the  $\Delta$ -conductivity:

$$E = 210 - 3.7 \sigma_{\Delta}$$

### 4. Foam Index

Air flow rate and foam expansion ratio increased as foam index increased, but the back pressure ratio decreased.

The equation for expansion ratio is

$$E = 22.65 + 1.798 N$$

### 5. Corn Borer Control

The effects of the foam carrier method on corn borer control was a fair success in comparison with the sprayer method.



The foam with medium expansion ratio (  $30 < E < 35$  ) was better for an insecticide carrier for corn borer control.

## SUGGESTIONS FOR FUTURE RESEARCH

1. Design a foam meter, by using some electrical devices and the principle of foam electrical conductivity to classify foams.
2. Analyze the quantity of insecticide that will drain out within the draining liquid and its behavior when applied on the corn leaves and in the leaf sheath.
3. Fit a gamma function or log normal distribution on the curves of foam drainage rate.
4. Redesign the foam generator that will produce the desired foams and can be so adjusted that foam bubbles can hit the right target even the wind speed is sometimes objectionable.
5. Perform a field test of foams for corn borer control even simply put foam bubbles on the corn plant by hand to detect the actual effect of the foam carrier method. And, simultaneously, find answers for the following problems:
  - a. How far the insecticide will get inside the corn sheath,
  - b. How fast the foam bubble will move on the plants when it hits the tilted corn leaves,
  - c. What type of foam is economical on corn borer control?

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## APPENDIX A. ANOVA TABLES FOR EXPANSION RATIO

Table 10. Air flow rate was fixed at 3.1 cfm

Mean: 126.38 C.V.: 3.862%

Source of Variation	Degree of Freedom	Mean Square	F-Test	
Replicates	2	17.858	--	
Foams-F0, F8, F4 (F)	2	187.575	7.871	**
Pressure ( $P_\ell$ )	5	3,103.984	130.252	**
F x $P_\ell$	10	18.771	0.787	ns <sup>a</sup>
Error	34	23.830		
Corrected total	53	319.410		

<sup>a</sup> Non-significant.

\*\* Significant difference at the 0.5% level.

Table 11. Liquid pressure was fixed at 40 psi

Mean: 163.57 C.V.: 6.30%

Source of Variation	Degree of Freedom	Mean Square	F-Test	
Replicates	2	44.580	--	
Foams-F0, F8, F4 (F)	2	106.100	0.999	ns <sup>a</sup>
Air flow rate ( $A_f$ )	3	53,014.041	499.196	**
F x $A_f$	6	132.996	1.252	ns
Error	22	106.199		
Corrected total	35	4,642.224		

<sup>a</sup> Non-significant.

\*\* Significant difference at the 0.5% level.



## APPENDIX B. EQUATIONS FOR THE DRAINED LIQUID

Table 12. Regression equations for the drained liquid of Fomex and AG-foams with or without insecticide Furadan

Types of Foams	Air Flow Rate, cfm	Equations <sup>a</sup>	R <sup>2</sup>
F0	1.6	$\ln Q = -5.21 + 3.36 \ln T - 0.26(\ln T)^2$	0.9229
F0	3.1	$\ln Q = -50.06 + 20.32 \ln T - 1.90 (\ln T)^2$	0.9858
F0	4.1	$\ln Q = -31.78 + 10.69 \ln T - 0.75 (\ln T)^2$	0.9052
F0	6.0	$\ln Q = 8.74 - 9.30 \ln T + 1.54 (\ln T)^2$	0.8612
A0	1.6	$\ln Q = -3.22 + 3.04 \ln T - 0.26 (\ln T)^2$	0.9948
A0	3.1	$\ln Q = -9.37 + 4.70 \ln T - 0.38 (\ln T)^2$	0.9982
A0	4.1	$\ln Q = 59.43 + 20.05 \ln T - 2.44 (\ln T)^2$	0.9718
A0	6.0	$\ln Q = -54.96 + 22.80 \ln T - 2.19 (\ln T)^2$	0.9788
F8	1.6	$\ln Q = -4.27 + 3.28 \ln T - 0.27 (\ln T)^2$	0.9570
F8	3.1	$\ln Q = -25.55 + 10.99 \ln T - (\ln T)^2$	0.7420
F8	4.1	$\ln Q = -30.52 + 11.75 \ln T - (\ln T)^2$	0.8772
F8	6.0	$\ln Q = -16.06 + 2.86 \ln T - 0.14 (\ln T)^2$	0.8729

<sup>a</sup> Units can be found in the notation section.



## APPENDIX C. EQUATIONS FOR FOAM CONDUCTIVITY

Table 13. Equations for the electrical conductivity of foams--  
liquid pressure was fixed at 40 psi

Type of Foam	Air Flow Rate, cfm	Equations <sup>a</sup>	R <sup>2</sup>
F0	1.6	$\ln \sigma = 4.49 - 0.01 T$	0.9359
F0	3.1	$\ln \sigma = 3.79 - 0.006 T$	0.9742
F0	4.1	$\ln \sigma = 3.53 - 0.0044 T$	0.9562
F0	6.0	$\ln \sigma = 3.24 - 0.0028 T$	0.9143
A0	1.6	$\ln \sigma = 3.86 - 0.0114 T$	0.9811
A0	3.1	$\ln \sigma = 3.57 - 0.009 T$	0.9909
A0	4.1	$\ln \sigma = 3.44 - 0.0078 T$	0.9574
A0	6.0	$\ln \sigma = 3.31 - 0.0067 T$	0.9759
F8	1.6	$\ln \sigma = 4.50 - 0.0113 T$	0.8670
F8	3.1	$\ln \sigma = 3.83 - 0.0077 T$	0.9125
F8	4.1	$\ln \sigma = 3.44 - 0.0052 T$	0.9138
F8	6.0	$\ln \sigma = 3.06 - 0.0034 T$	0.9242

<sup>a</sup> Units can be found in the notation section.

APPENDIX D. ANOVA TABLES FOR  $\Delta$ -CONDUCTIVITY

Table 14. Air flow rate was fixed at 3.1 cfm

Mean: 25.304 C.V.: 3.15%

Source of Variation	Degree of Freedom	Mean Square	F-Test
Replicates	2	0.058	--
Foams-F0, F8, F4 (F)	2	27.708	43.62 **
Pressure ( $P_\ell$ )	5	472.316	743.82 **
F x $P_\ell$	10	1.474	2.32 *
Error	34	0.635	
Corrected total	53	46.291	

\*\* Significant difference at the 0.5% level.

\* Significant difference at the 1% level.

Table 15. Liquid pressure was fixed at 40 psi

Mean: 20.73 C.V.: 3.381%

Source of Variation	Degree of Freedom	Mean Square	F-Test
Replicates	2	0.085	--
Foams-F0, F8, F4 (F)	2	28.995	59.05 **
Air flow rate ( $A_f$ )	3	498.261	1,014.78 **
F x $A_f$	6	0.684	1.39 ns <sup>a</sup>
Error	22	0.491	
Corrected total	35	44.796	

<sup>a</sup> Non-significant.

\*\* Significant difference at the 0.5% level.

\* Significant difference at the 1% level.

## APPENDIX E. ANOVA TABLES FOR PICTURE INDEX

Table 16. Analysis of variance of air flow rates related to the index number with liquid pressure at 40 psi

Mean: 1.047 C.V: 31.34%

Source of Variation	Degree of Freedom	Mean Square	F-Test
Replicates	2	0.170	--
Percentage ( $\alpha_f$ )	2	1.177	10.925 ***
Index (N)	5	7.861	72.971 ***
$\alpha_f \times N$	10	0.139	1.293 ns <sup>a</sup>
Error	34	0.108	
Corrected total	53	0.888	

<sup>a</sup> Non-significant.

\*\*\* Significant difference at 0.05% level.

Table 17. Analysis of variance of back pressure ratio related to the index number with liquid pressure at 40 psi

Mean: 2.980 C.V.: 21.28%

Source of Variation	Degree of Freedom	Mean Square	F-Test
Replicates	2	0.672	--
Percentage ( $\alpha_f$ )	2	15.637	38.80 ***
Index (N)	5	36.645	96.00 ***
$\alpha_f \times N$	10	1.236	3.06 *
Error	34	0.403	
Corrected total	53	4.564	

\*\*\* Significant difference at the 0.05% level.

\* Significant difference at the 5% level.

Table 18. Analysis of variance of expansion ratio related to the index number with liquid pressure at 40 psi

		Mean:49.91	C.V.:11.18%
Source of Variation	Degree of Freedom	Mean Square	F-Test
Replicates	2	257.419	--
Percentage ( $\alpha_f$ )	2	301.301	9.678 ***
Index (N)	5	5,371.878	172.558 ***
$\alpha_f \times N$	10	120.140	3.859 **
Error	34	31.131	
Corrected total	53	570.503	

\*\*\* Significant difference at the 0.05% level.

\*\* Significant difference at the 1% level.

## APPENDIX F. PRIMARY DATA FOR CORN BORER CONTROL

Table 19. Primary data for corn borer control. The unit is in cavities per twenty corn plants

Trt No.	Foam <sup>a</sup> Type	Liquid Rate, gpa	$\alpha_f$ %	Replicates(cavities/20 plants)			
				I	II	III	IV
1	A	10	0.25	25	41	14	14
2	A	10	0.50	33	27	12	16
3	A	20	0.25	30	24	18	23
4	A	20	0.50	54	24	21	33
5	B	10	0.25	55	21	24	21
6	B	10	0.50	41	22	27	27
7	B	20	0.25	53	26	32	28
8	B	20	0.50	23	27	41	26
9	C	10	0.25	37	28	27	51
10	C	10	0.50	18	28	24	19
11	C	20	0.25	37	39	32	25
12	C	20	0.50	49	26	28	29
13	S	10	0.25	12	18	27	17
14	S	10	0.50	36	13	13	32
15	S	20	0.25	26	12	6	16
16	S	20	0.50	20	31	13	18
17	CK	--	----	57	42	42	42
18	CK	--	----	58	52	48	49
26	CK	--	----	44	37	55	63

- <sup>a</sup> Foam A = expansion ratio--30-35.  
 Foam B = expansion ratio-- > 100.  
 Foam C = expansion ratio-- < 20.  
 S = sprayer method.  
 CK = check plots.